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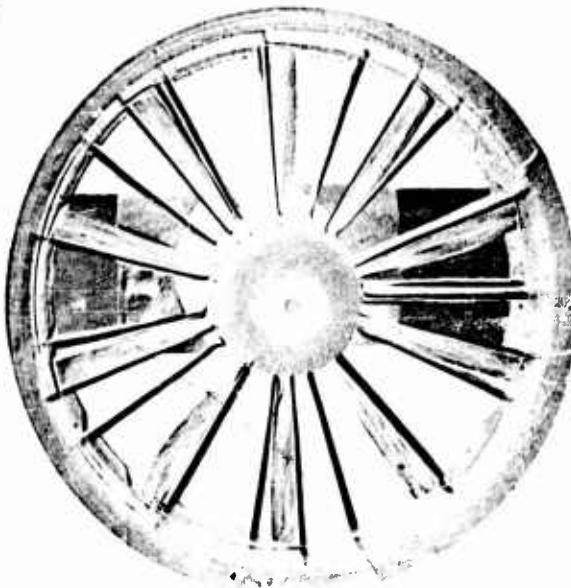
UNIVERSITY OF WICHITA
ENGINEERING RESEARCH
REPORT NO. 213-15

SHROUDED PROPELLER INVESTIGATIONS:
PROPELLER TIP CLEARANCE EFFECTS

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By: Vernon O. Hoehne
and
Hans Hoffman

Prepared for
Office of Naval Research
Air Branch
Washington, D.C.
under
Contract NONR 201(01)



April 1961
Wichita, Kansas

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DEPARTMENT OF ENGINEERING RESEARCH



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SHROUDED PROPELLER INVESTIGATIONS:
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SUMMARY

Wind tunnel tests were conducted on a shrouded propeller model in which the propeller diameter was varied for the purpose of measuring the effects of tip to shroud clearance. The basic model tested contained a four-bladed variable pitch propeller operating within a 0.50 chord/diameter ratio shroud. To assist in studying the effect of annulus area on tip clearance, two models having 0.30 and 0.40 hub/tip diameter ratio center-bodies were tested over roughly the same range of propeller tip clearances.

Performance of the models was measured throughout a range of advance ratios from zero to roughly 2.20 at several propeller blade pitch settings at zero angle of attack only. Results are presented in the form of force and power coefficients and efficiency varying with propeller tip clearance and rotational speed for forward and static flight conditions.

INTRODUCTION

During the past several years the University of Wichita, Department of Engineering Research has been exploring the aerodynamic characteristics of shrouded propellers using a systematic set of models. The first units tested under the program were highly loaded models having high solidity propeller and exit vane stages. The experimental results of these models have been reported in Ref. 1. The second units tested under this program were lower loaded models having propeller solidities within the range from 0.05 to 0.20. These models, containing 2, 4 and 6-bladed propellers, were designed by the methods outlined in Ref. 2. Test results of the 2 and 4-bladed models are reported in Report Nos. 213-11 and 213-12 of Ref. 3.

During the test program, the need for investigating the effect of various geometric parameters on the performance of shrouded propellers became evident. The parameters chosen for study were: relative size of unit centerbody, propeller tip clearance, shroud chord, shape of shroud exit and propeller blade chord effects. The effect of centerbody relative size is reported in Report No. 213-13 and the effect of shroud exit shape in Report No. 213-16 of Ref. 3. This report includes the effect of propeller tip clearance.

Two basic shrouded propeller models were used to test the effect of propeller tip clearance. Both models were identical, except the propeller centerbody diameter was 30% of the shroud inner diameter in one and 40% in the other. Tests of these models were performed in the 7 x 10 foot low-speed University of Wichita wind tunnel (Ref. 4). The basic model configuration included a 4-bladed variable pitch propeller, a shroud with variable inlet geometry having a 1.16-foot inner diameter and a chord/diameter ratio of 0.50. The propeller blade airfoil section was an RAF-6, Section E. Seven exit vanes, which varied from root to tip in camber and thickness, were provided to remove the rotational velocity component leaving the plane of the propeller.

The wind tunnel Test arrangement of the model is show in Figs. 1 and 2. A dimensional description of the shrouds are included in Fig. 3.

NOMENCLATURE

c	Shroud chord, 0.58 ft
C _P	Power coefficient, $\frac{P}{\rho n^3 d^5}$
C _T	Thrust coefficient, $\frac{T}{\rho n^2 d^4}$
d	Shroud inside diameter, 1.16 ft
h	Centerbody diameter, ft
J	Advance ratio, $\frac{V_o}{nd}$

M	Shrouded propeller figure of merit = $0.5 \frac{T}{P} \sqrt{\frac{T}{\rho A}}$
n	Rotational speed, rps
P	Power, $\frac{\text{ft-lb}}{\text{sec}}$
P_c	Power coefficient, $\frac{P}{qV_0 S}$
q	Free stream dynamic pressure, psf
r	Local blade radius, ft
Δr	Propeller tip to shroud surface clearance, inches
S	Projected side area of inside shroud surface, $cd \text{ ft}^2$
T	Thrust - parasite drag, lb
T_c	Thrust coefficient, $\frac{T}{qS}$
T_S	Shroud thrust, lb
T_{CS}	Shroud thrust coefficient, $\frac{T_S}{qS}$
V_0	Tunnel velocity, fps
θ_p	Blade pitch setting at $\frac{r}{R} = 0.8$, degrees
δ	Boundary layer thickness, inches
η	Propulsive efficiency, $\frac{TV_0}{P}$
ρ	Air density, slugs/ ft^3

TEST APPARATUS AND PROCEDURE

For tests at static and forward flight conditions, the model was mounted in the wind tunnel as shown in Fig. 1 and described in Report No. 213-2 of Ref. 1. Shroud thrust and motor torque were measured by strain gage balance systems from which an electrical signal was digitized by a modified Brown recorder and read out on a Clary printer. Six components of moments and forces were manually read on the tunnel balance indicators.

The testing procedure consisted of operating the tunnel at a constant preselected tunnel dynamic pressure and driving the model propeller at successively increasing rotational speeds. The tunnel dynamic pressures and propeller rotational speeds used during the tests are as follows:

<u>Dynamic Pressure psf</u>	<u>Average Tunnel Velocity, fps</u>	<u>Propeller RPM</u>	
2.1	44	WM	4050
8.4	88	1800	4950
21.1	140	2400	6000
		3000	7500
		3450	9600

With few exceptions, all propeller rotational speeds were run at each tunnel dynamic pressure setting. In all cases, the minimum test propeller RPM was windmilling. The maximum propeller RPM was reduced only when it became apparent that further testing could damage the model.

At forward flight conditions, all tests were performed with the model axis aligned with the tunnel wind axis.

At static test conditions, the models were positioned in the wind tunnel with their axes yawed approximately 90° to the tunnel longitudinal axis so that static thrust was measured on the side force component of the tunnel balance system. A large entrance door (7 x 20 feet) providing access to the wind tunnel throat was opened and the model faced toward this opening. The exact angular position of the models was set by performing a preliminary test with no tunnel wind at a sequence of angles near 90° to the tunnel throat axis, and determining the angle at which zero force was indicated on the wind tunnel drag balance which remained aligned with the wind axis. This adjustment split the model jet at the tunnel wall causing a minimum of tunnel flow.

At the conclusion of each test sequence with one tip clearance, the model propeller was removed from the model, the blade pitch angle adjusted so that the tip section angle was 90° to the propeller axis, and the blade tips ground to a new value of tip clearance. During the grinding operation the entire propeller assembly was mounted on a dummy shaft which was mounted between the head and tail stock of a lathe. The tips of the blades were ground to a specific clearance by rotating the propeller assembly so that each blade tip came in contact with a

grinder mounted on the lathe compound. At the completion of the grinding operation the propeller blade pitch angle was reset to a test angle, the assembly reinstalled in the model and testing resumed. By following this procedure, only one set of propeller blades was required for each model.

CORRECTIONS

The only jet boundary correction considered during these tests was jet blockage which was automatically accounted for during the test runs by a properly located pitot-static tube.

The method of correction for jet blockage had been evolved during earlier shrouded propeller investigations. The philosophy behind the method of corrections is that since jet blockage is expressed in terms of the ratio of free-stream air velocity of the model operating in free air to the tunnel air velocity at the model, it was surmised that the blockage term could be experimentally evaluated by measuring the velocity in a region adjacent to the model where the air streamlines were straight (no pressure gradient) and comparing this to tunnel indicated velocity. This had the added advantage that it automatically accounted for the tunnel throat dynamic pressure calibration factor.

During earlier phases of these shrouded propeller investigations, instrumentation was installed in the wind tunnel to measure the variation of total and static pressure in the area between the model and tunnel wall at all test velocities and model thrust settings. The measured static pressures were plotted against pressure tube location relative to the model centerline and tunnel walls. The region in which static pressure became invariant with rake position was determined and used as the area in which freestream dynamic pressure was measured. This dynamic pressure was then compared to the dynamic pressure indicated by the conventional tunnel system yielding a jet blockage correction term. This blockage term was plotted as a function of thrust (Ref. 1).

During these tests, a pitot-static tube was mounted in the area of invariant static pressure and the tunnel dynamic pressure adjusted with reference to its indication. In this way the tunnel blockage correction and dynamic pressure calibration factor were automatically applied to the data without extensive computation.

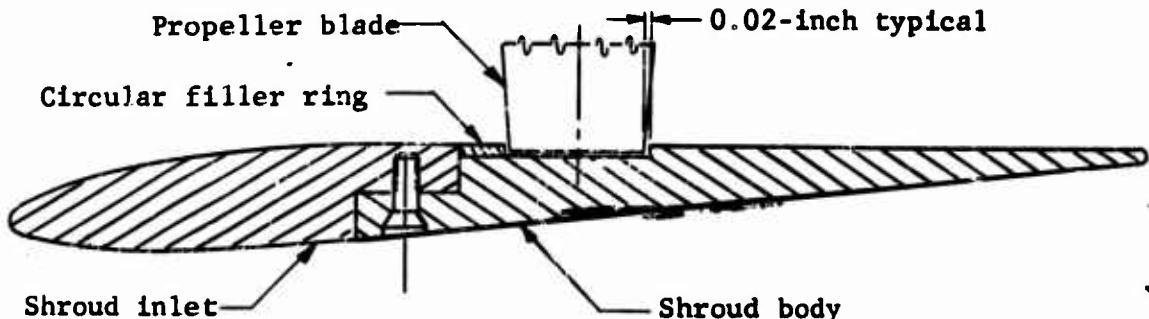
RESULTS AND DISCUSSION

Although six-components of force and moment data, along with propeller torque and shroud thrust, were recorded during the test program, only those data that showed significant variation with tip clearance are presented in this report. These data include power, total and shroud thrust and a combination of total thrust and power in propulsive efficiency. These data are presented in coefficient form common to aircraft nomenclature and are referenced to the freestream velocity. Static flight data coefficients are based on propeller rpm and diameter.

The force and power data in coefficient form are plotted against the dimensional parameters of tip clearance (Δr) in inches, freestream velocity in fps, and propeller rotational speed in rpm. Attempts were made to relate the changes in force and power coefficients to a ratio of propeller area to shroud inner diameter area, but no correlation between the data from the models having different annulus areas existed.

The models were tested at $\alpha = 0^\circ$ and $\beta = 20^\circ, 30^\circ$ and 40° only. In general, only the high speed inlet (Fig. 2) shroud configuration was tested at forward flight conditions and the low speed inlet (Fig. 1) shroud configuration tested at static flight conditions. A non-diffused shroud afterbody was installed throughout the tests.

For tests at negative values of tip clearance, a groove, 0.04-inch in depth, was machined in the inner periphery of the shroud. A circular filler ring was installed to provide a



continuous shroud surface to a clearance of 0.02 inches with the propeller blade at each of the test values of blade pitch angle as shown in the sketch.

In general, tip clearance values near 0.10 to 0.15 inches caused the greatest change in power required, with this tendency decreasing as propeller blade pitch angle increased. Thrust also showed the same variation with tip clearance, except to a lesser degree. To better understand the mechanism of these rather sudden changes with tip clearance, the boundary layer thickness at the plane of the propeller was calculated as a function of thrust coefficient with a turbulent boundary layer assumed to exist from the shroud leading edge to the propeller plane. The annulus velocity was calculated using the methods outlined in Ref. 2 and the boundary layer thickness was calculated using the equation:

$$\delta = \frac{0.37x}{\sqrt{\frac{5}{R_x}}}$$

where x is the distance from the shroud leading edge to the propeller plane and R_x is the Reynolds number based on this distance. The results of these calculations are plotted in Fig. 4 for static flight conditions and Fig. 5 for forward flight conditions. The boundary layer thicknesses shown in these figures is not exact since it is based on flow over a flat plate. The shroud surface, rather than being flat, is convex to the fluid flow. According to Schlichting (Ref. 5), curvature of the type existing in the inlet to the shroud causes the boundary layer thickness to increase slightly. Therefore, the thicknesses shown in Figs. 4 and 5 are probably conservative in that they indicate smaller thicknesses than actually existed during the tests. Regardless of the exactness of these thicknesses, they do illustrate the point that power and thrust decrease significantly when tip clearance is roughly equal to boundary layer depth.

As discussed in Ref. 6, the tip of a propeller blade develops a blade-passage vortex and blade-tip-scraping vortex system which dissipates energy that could otherwise develop thrust. The strength of these vortex systems are a function of the depth to which the propeller blade tip penetrates the boundary layer. Also, since the axial flow velocity decreases with penetration into the boundary layer, the angle of attack of the portion of the blade tip in the boundary layer increases (see Ref. 2) causing an increase in drag and lift of the tip airfoil section. The effect of this increase in force components is more noticeable in power coefficient

because the force arm upon which torque is based is the greatest at the tip, causing an increase in torque and therefore power proportionally greater than the increase in thrust.

As a result of both the losses due to the blade tip vortex system, and the proportionally greater increase in power than increase in thrust within the boundary layer, propulsive efficiency generally is lower at tip clearances less than the boundary layer depth than it is with tip clearances greater than boundary layer depth (Fig. 13). The plots with an expanded efficiency scale ($\Omega_p = 30^\circ$) show that efficiency decreases markedly and then increases as tip clearance increases through the region of retarded flow in the boundary layer. These data indicate that for most efficient shrouded propeller operation, the tip clearance of the propeller should be roughly equal to the boundary layer depth at the propeller plane under cruising flight conditions. This, however, decreases the overall thrust of the unit for two reasons, the loss in propeller thrust and the loss in shroud thrust. Therefore, it appears that for most efficient operation and the highest possible disc loading, the boundary layer at the plane of the propeller should be removed. This does not, however, increase efficiency unless the power required for boundary layer removal is less than the power increase due to the presence of the boundary layer.

Considering the overall efficiency of the shrouded propeller unit, tip clearances roughly equal to boundary layer thickness relax the requirement for shroud rigidity. The larger the propeller tip clearance, the more the shroud inner surface can flex without contacting the propeller tips. Lowering the requirement for rigidity lowers the shroud weight and, therefore, the total weight of the shrouded propeller unit. This, coupled with the slight increase in propulsive efficiency realized with these tip clearances, yields a shrouded propeller unit having best efficiency at a lower structural weight. The penalty in thrust imposed by incorporating a larger tip clearance is offset to a great extent by the decrease in unit weight.

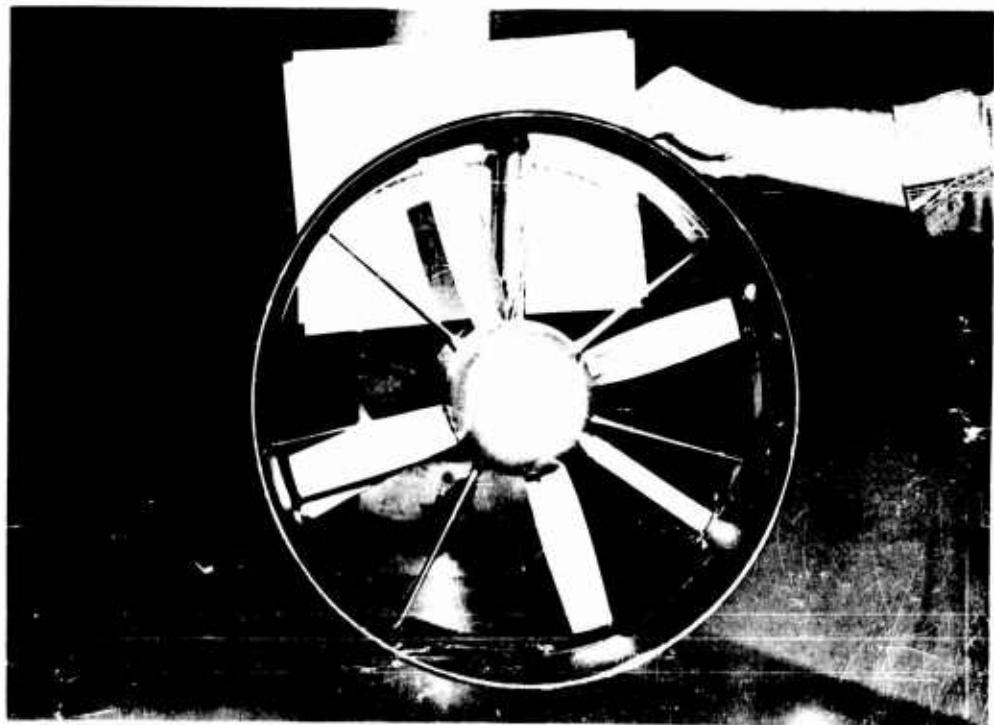
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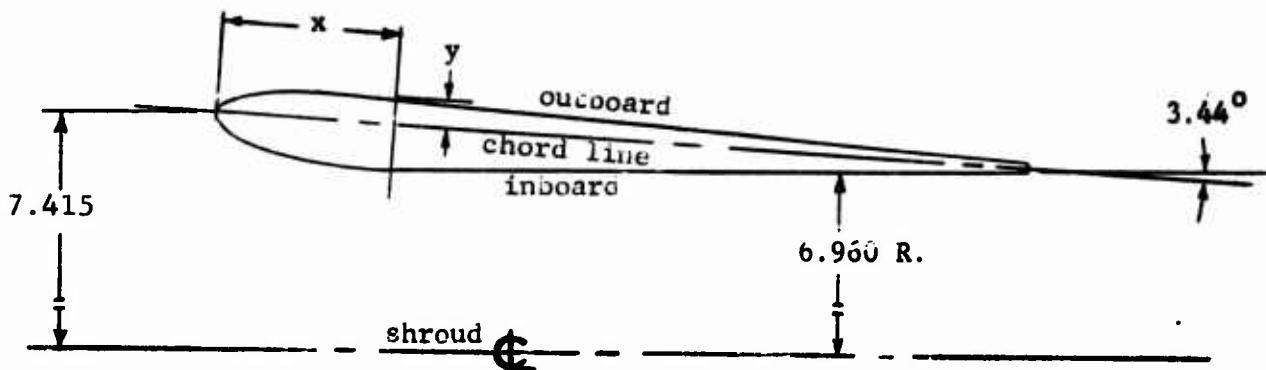
**Figure 1 - Test Model with 0.3 Tip/Hub Diameter Ratio
Centerbody and Low Speed Inlet**



**Figure 2 - Test Model with 0.4 Tip/Hub Diameter Ratio
Centerbody and High Speed Inlet**

SHROUD AND INLET ASSEMBLYHIGH SPEED INLET
NON-DIFFUSED EXIT

Inset diameter	14.83 inches
Diameter at propeller plane	13.92 inches
Exit diameter	13.92 inches
Shroud length	6.96 inches



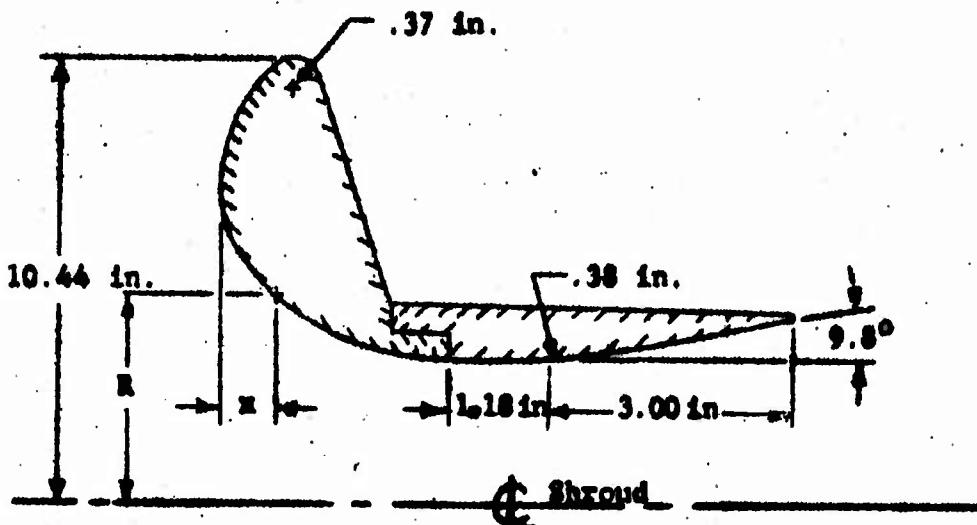
x/c (% Chord)	Section Ordinates y/c (Outb'd)	y/d (Inb'd)
1.25	1.28	1.50
2.50	1.75	2.15
5.0	2.32	2.98
7.5	2.71	3.57
10	2.98	4.03
15	3.19	4.57
20	3.18	4.82
25	3.14	4.84
30	3.04	4.69
40	2.68	4.06
50	2.31	3.45
60	1.93	2.83
70	1.54	2.22
80	1.17	1.63
90	.82	1.02
100	0	0

L.E. Radius r/c (% chord) = 0.89, T.E. Radius r/c (% chord) = 0.43

Figure 3.

SHROUD AND INLET ASSEMBLYLow Speed Inlet
Diffused Exit

Maximum inlet diameter	10.44 inches
Diameter at propeller plane	15.92 inches
Exit diameter	14.96 inches
Shroud chord	6.96 inches



Inlet Ordinates

x/c(%)	R/c(%)	x/c(%)	R/c(%)
12.00	150.0	14.14	107.1
8.39	148.4	19.89	104.1
5.52	145.2	25.63	102.0
2.64	140.7	28.51	101.3
1.32	137.6	31.38	100.7
0	130.0	34.25	100.3
1.32	122.4	37.12	100.1
2.64	119.3	40.0	100.0
5.52	114.8		
8.39	111.6		

Straight line segments aft of 40% chord station.

T.E. Radius - r/c(%) = 0.43

Figure 4.

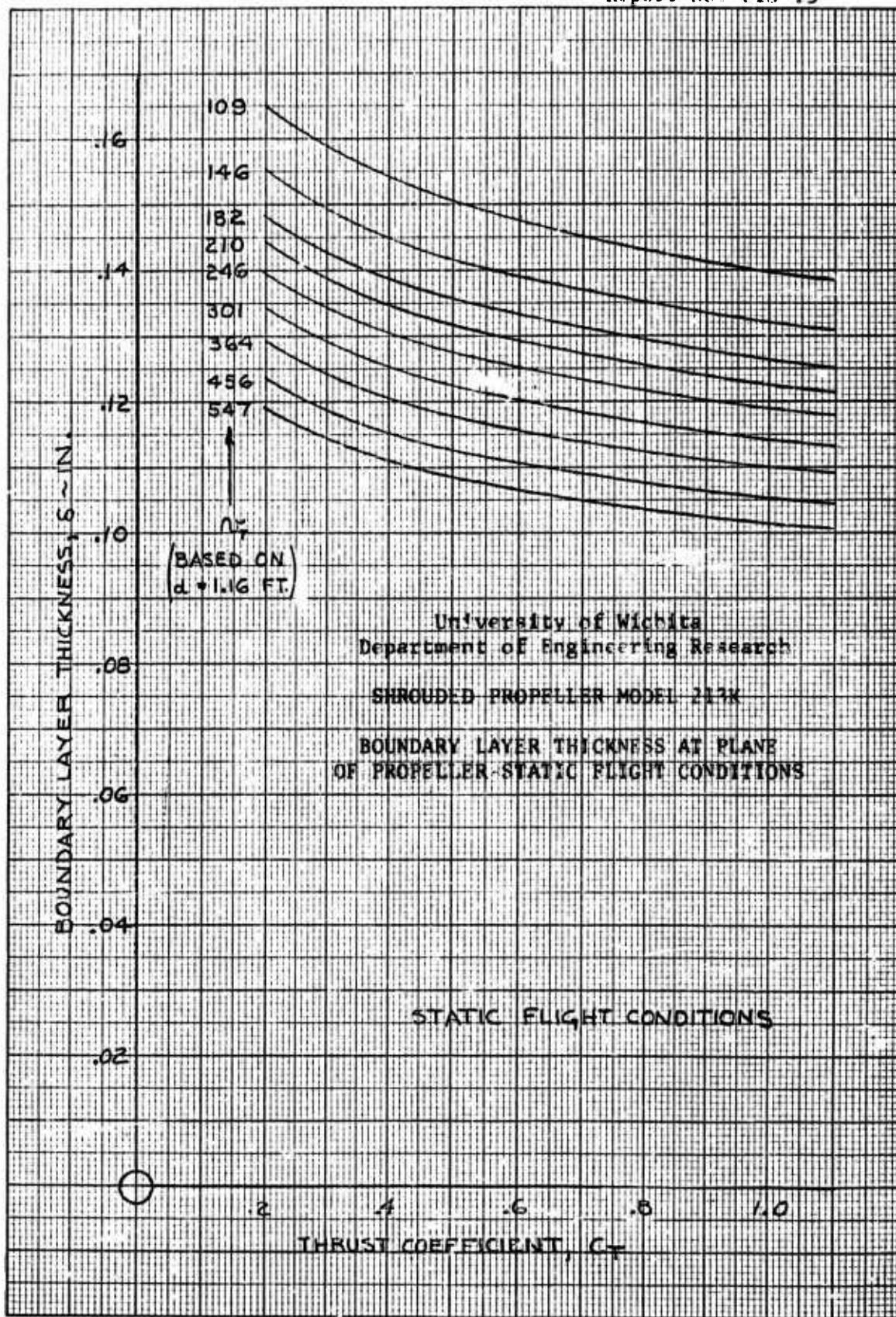


Fig. 4

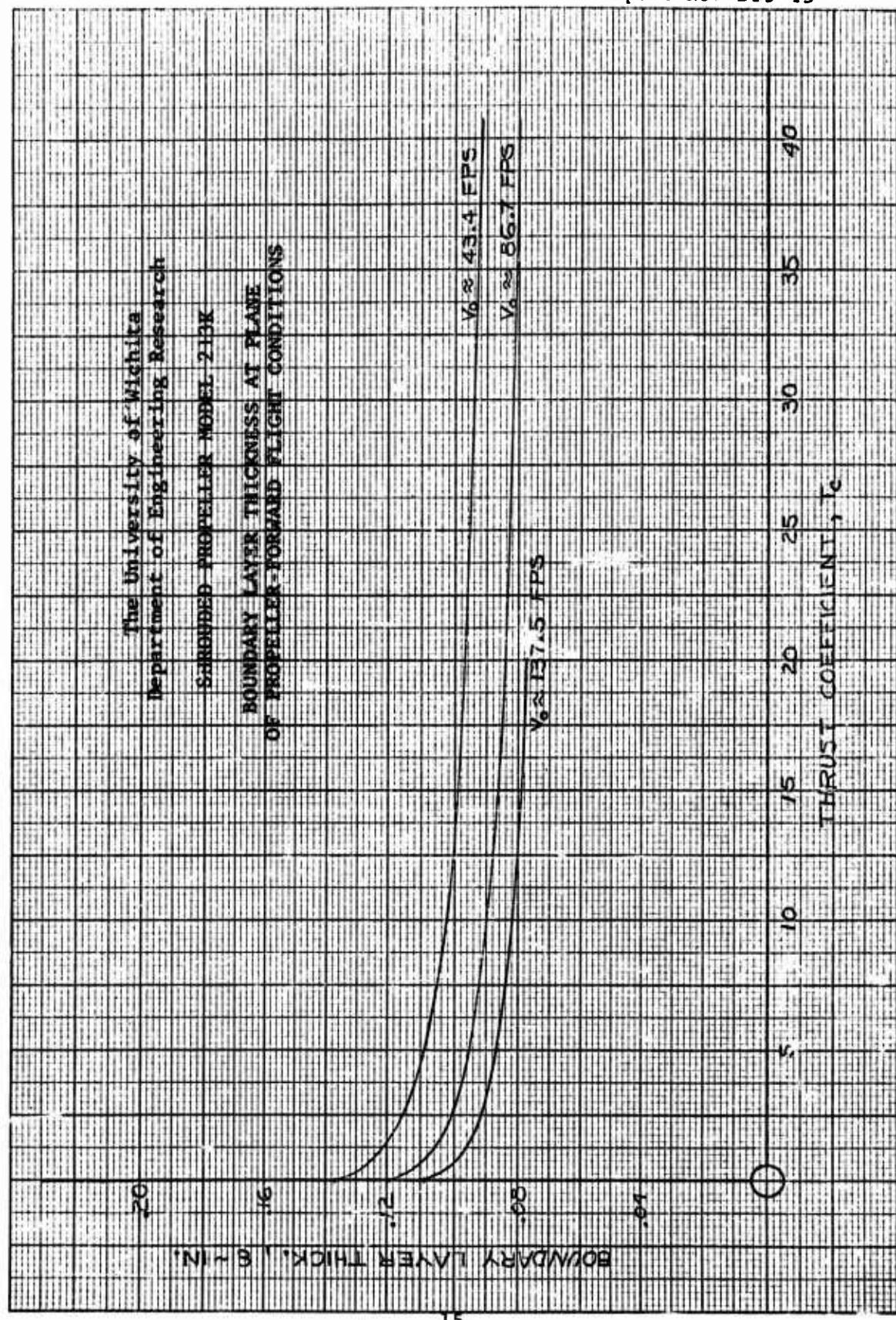


Fig. 5

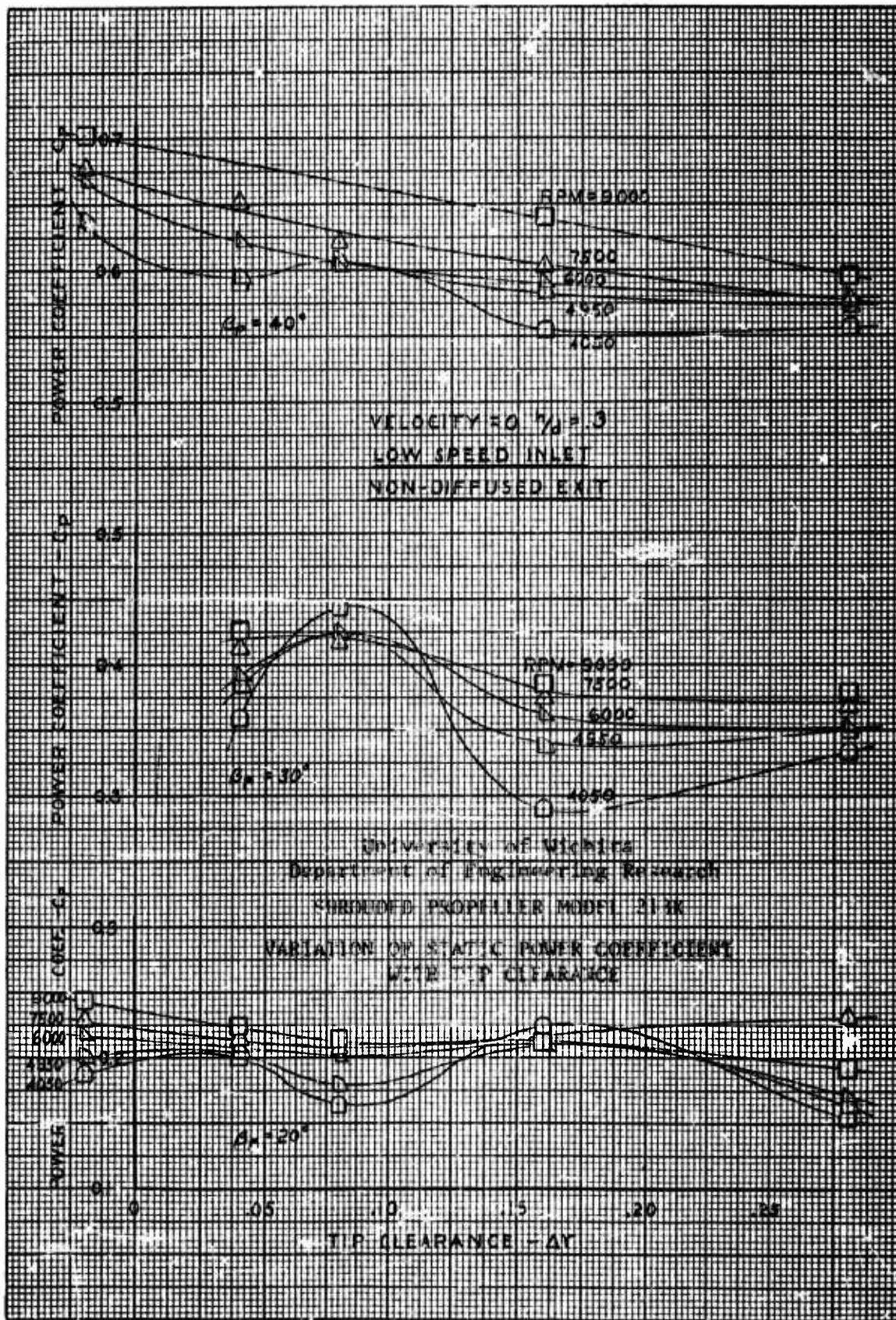
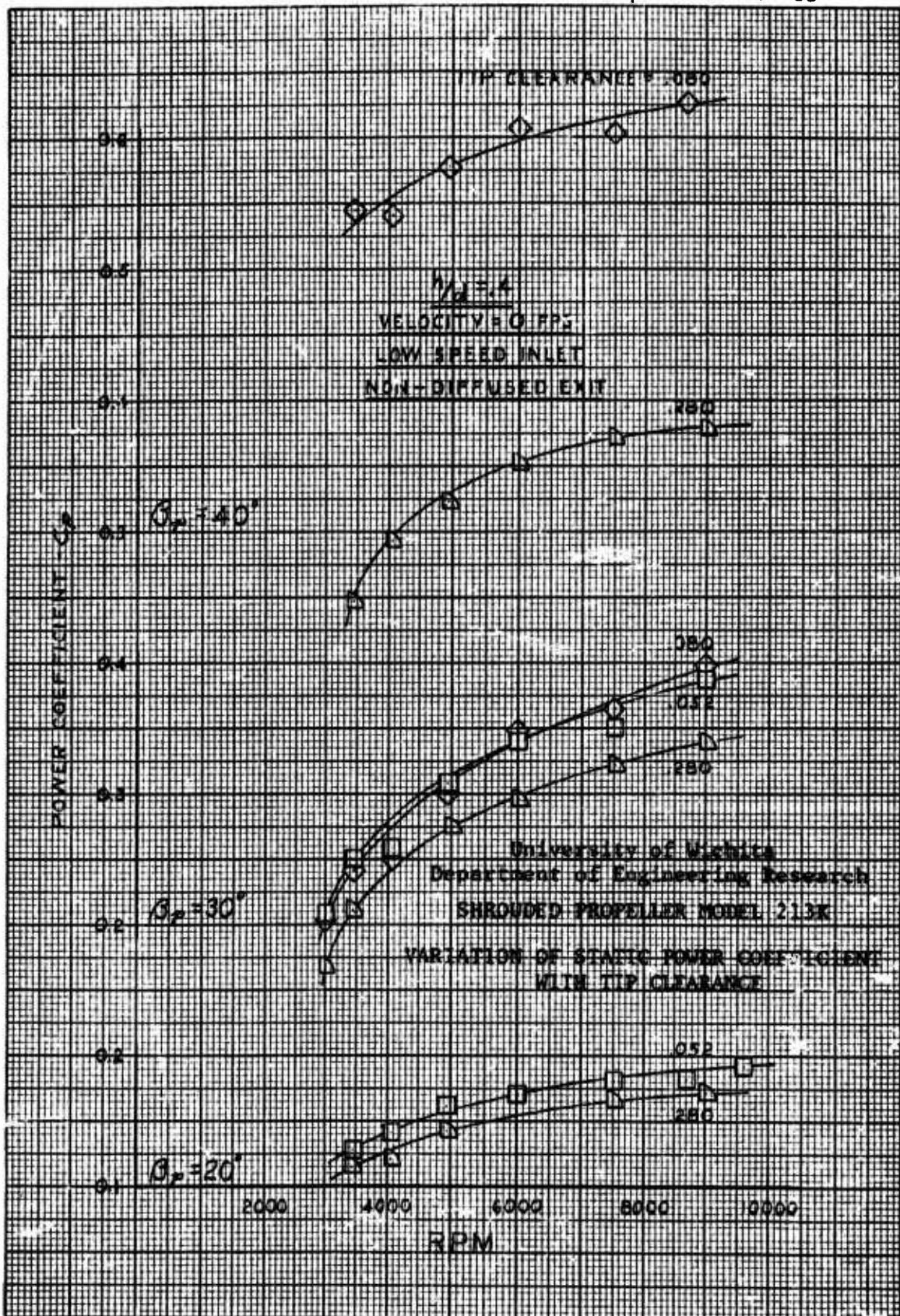


Fig. 6



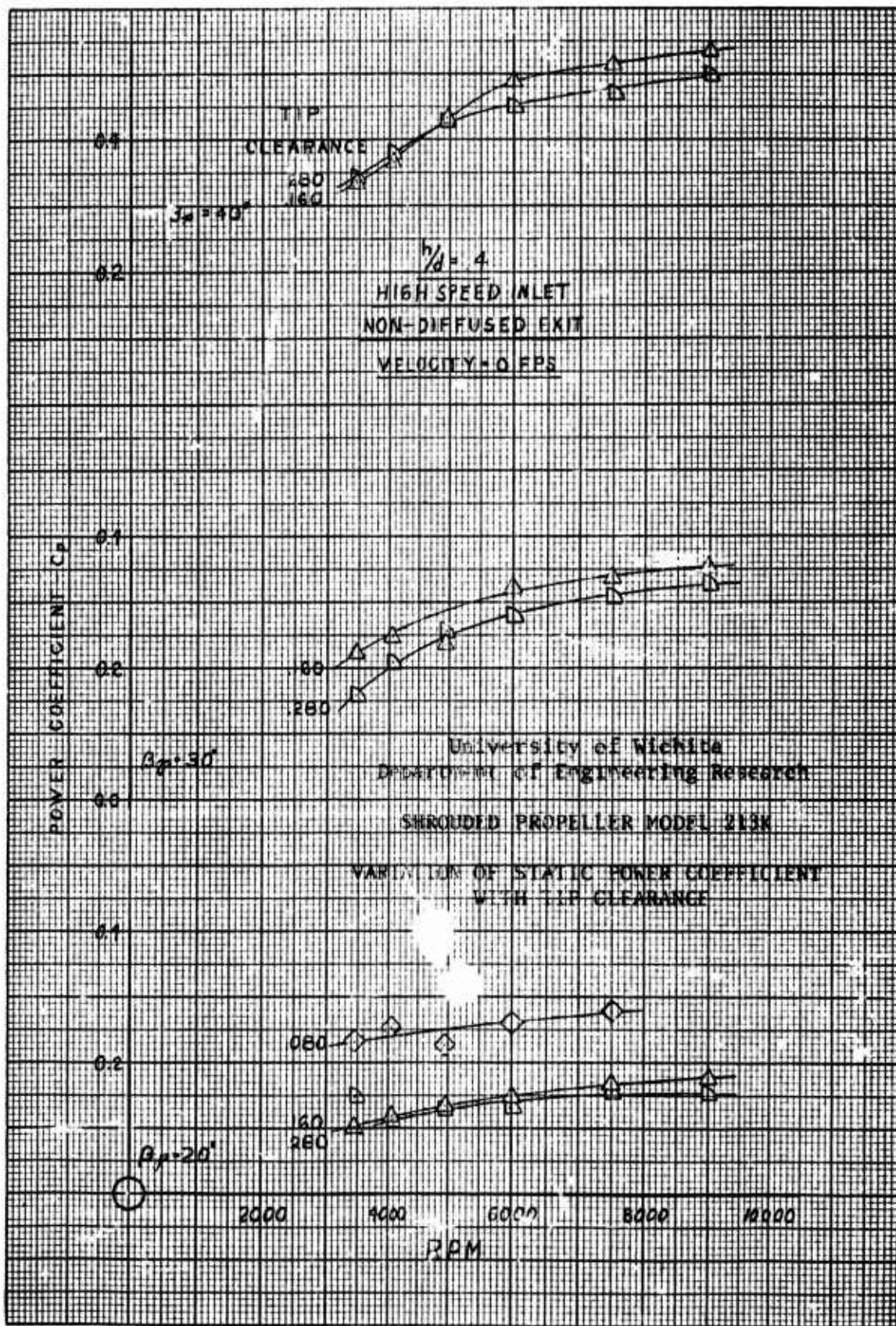
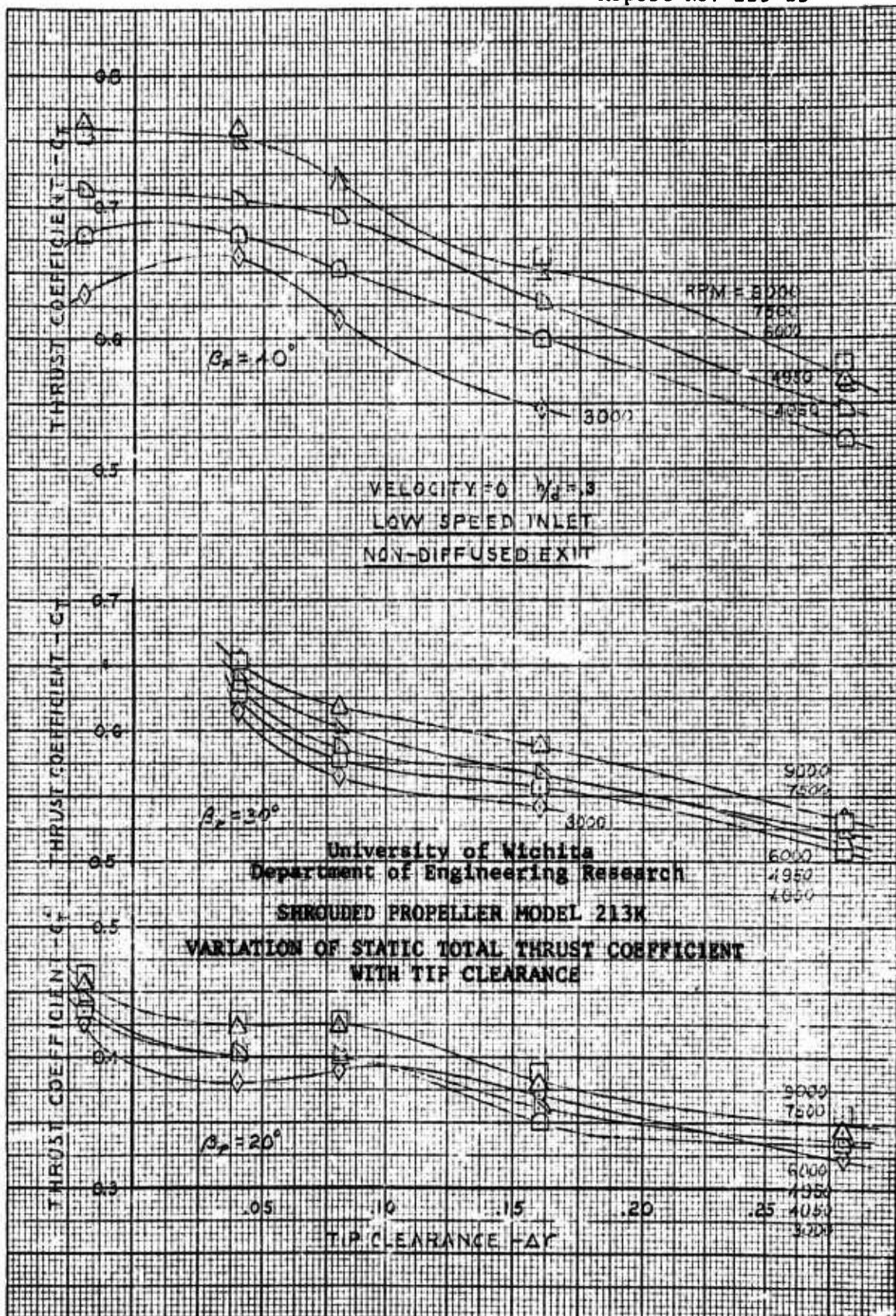


Fig. 6 (concluded)



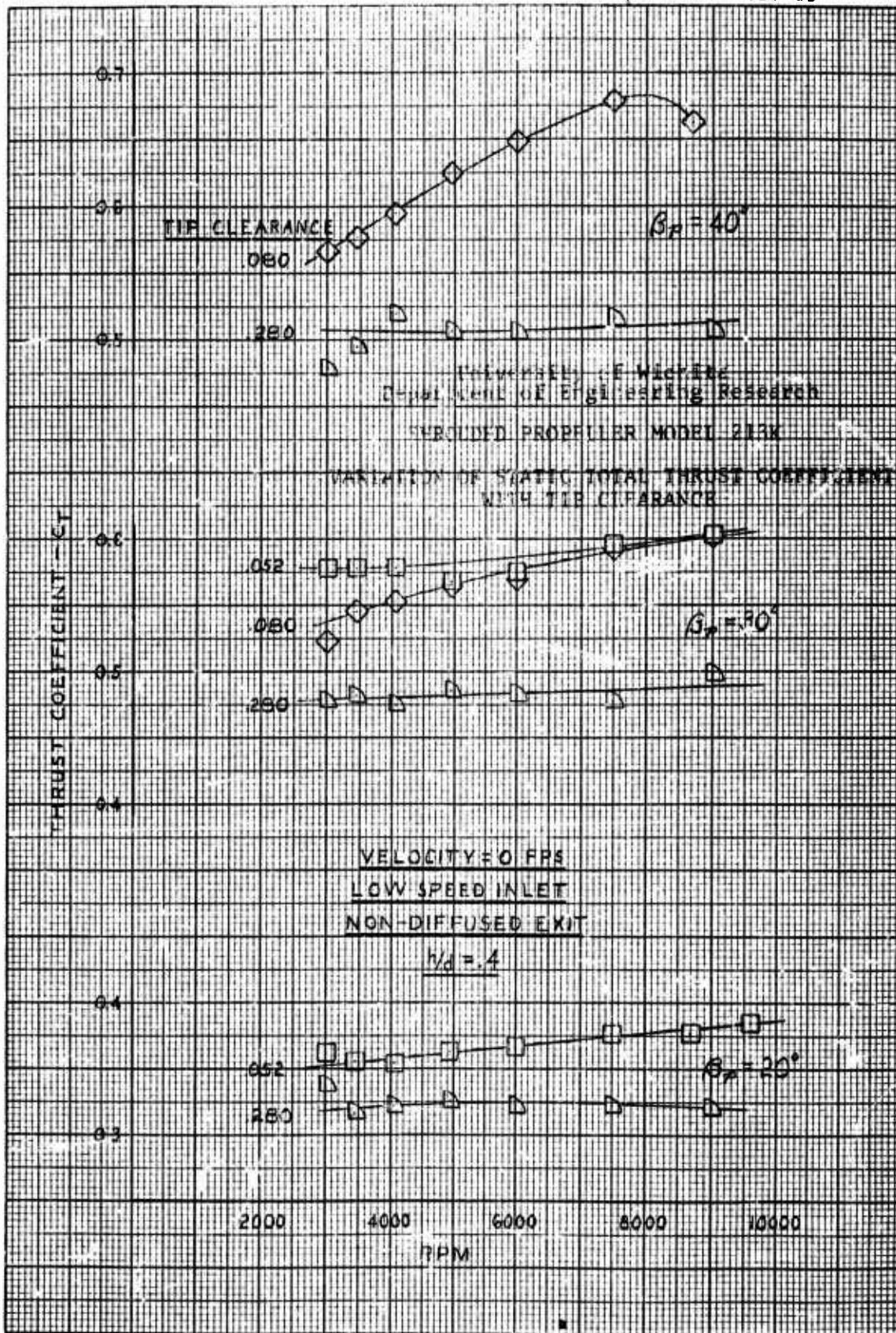
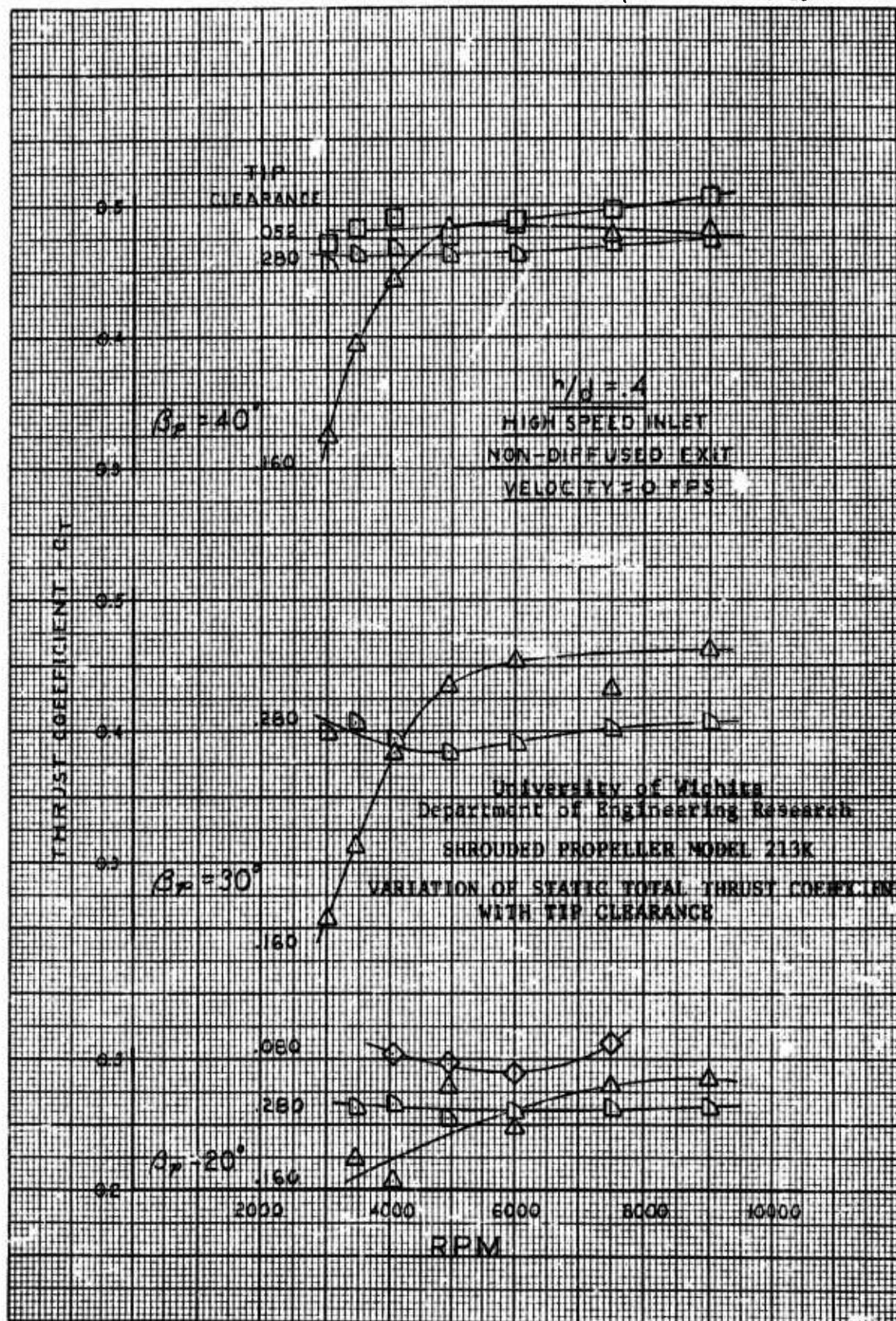


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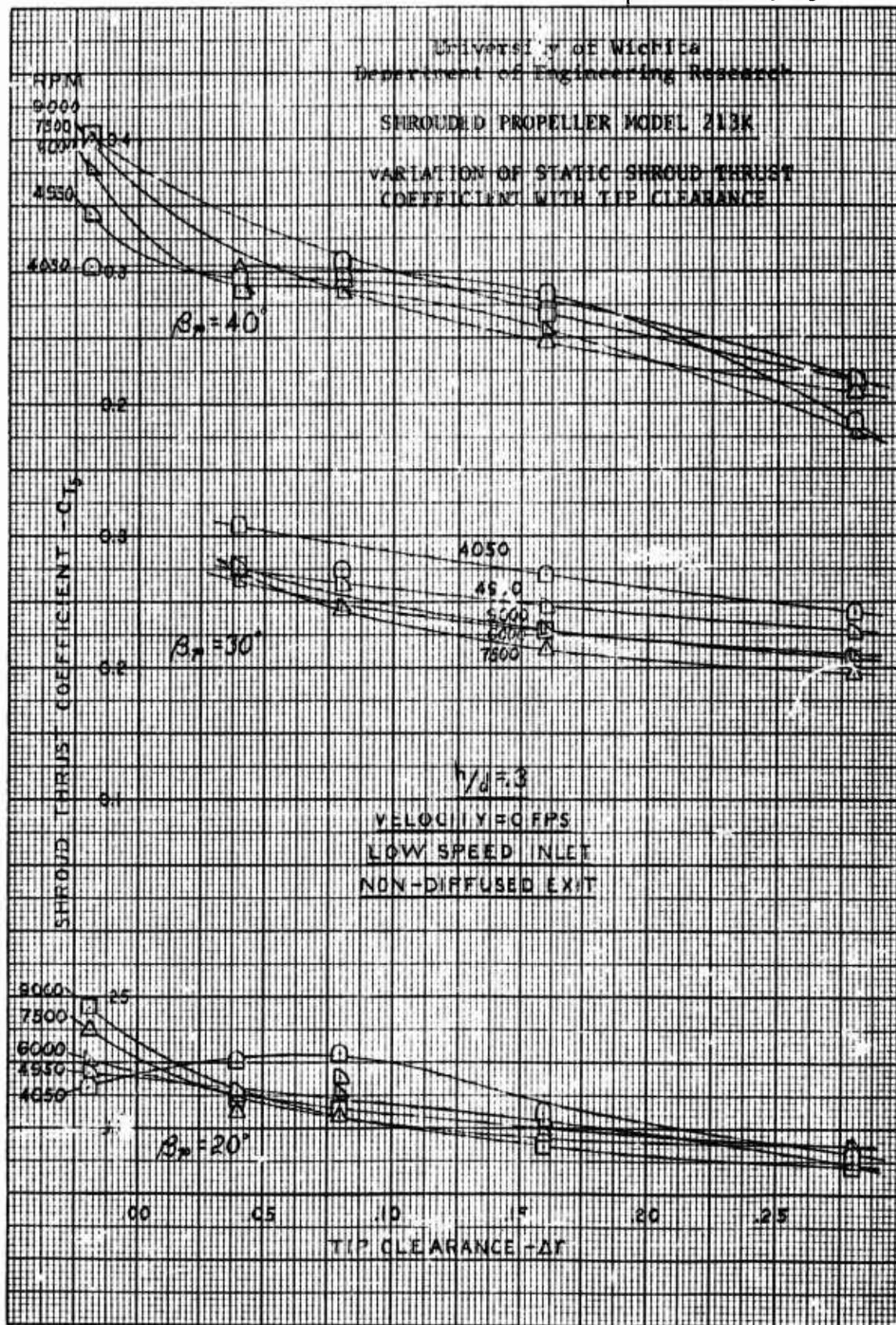
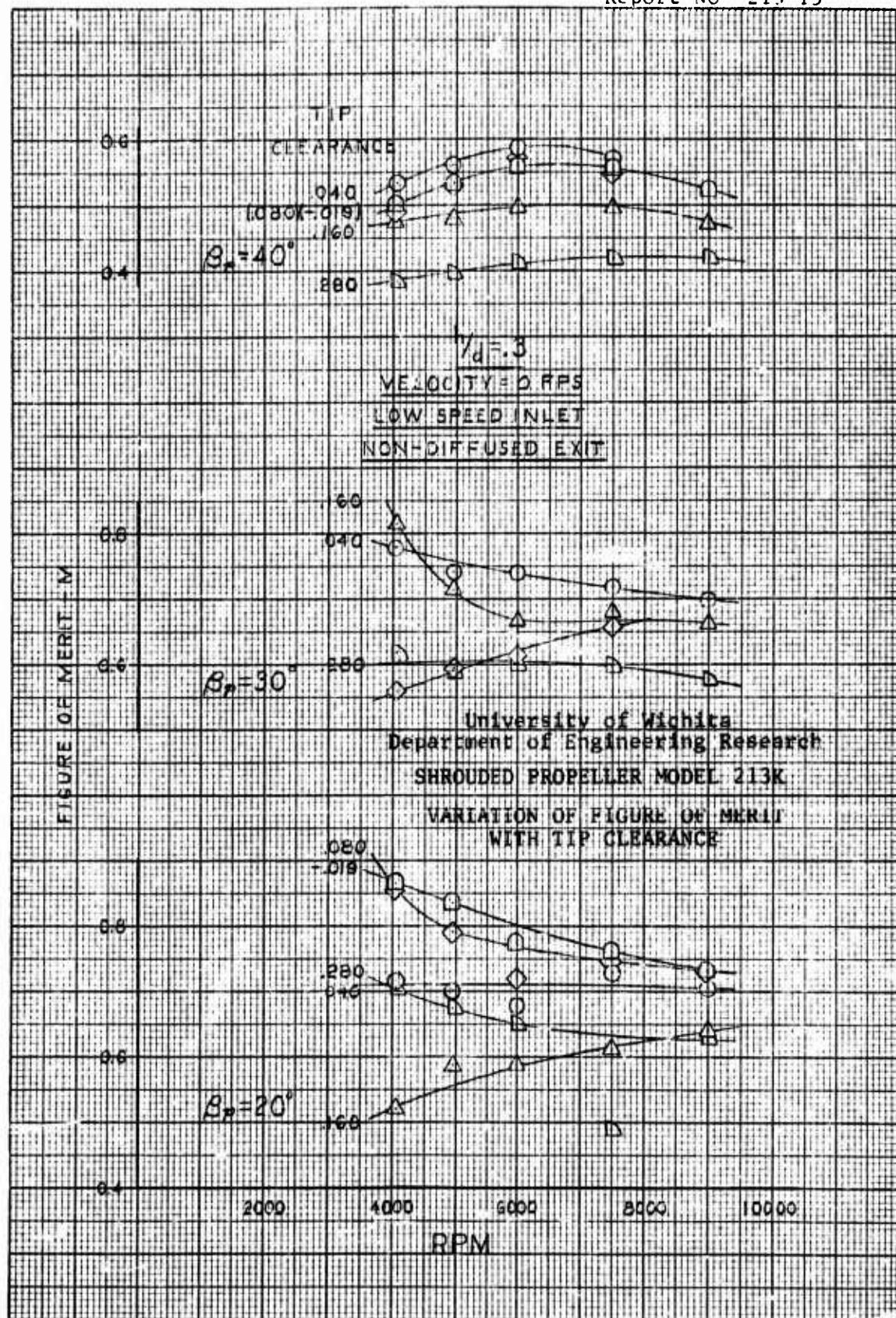


Fig 8



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SHROUDED PROPELLER MODEL 213K

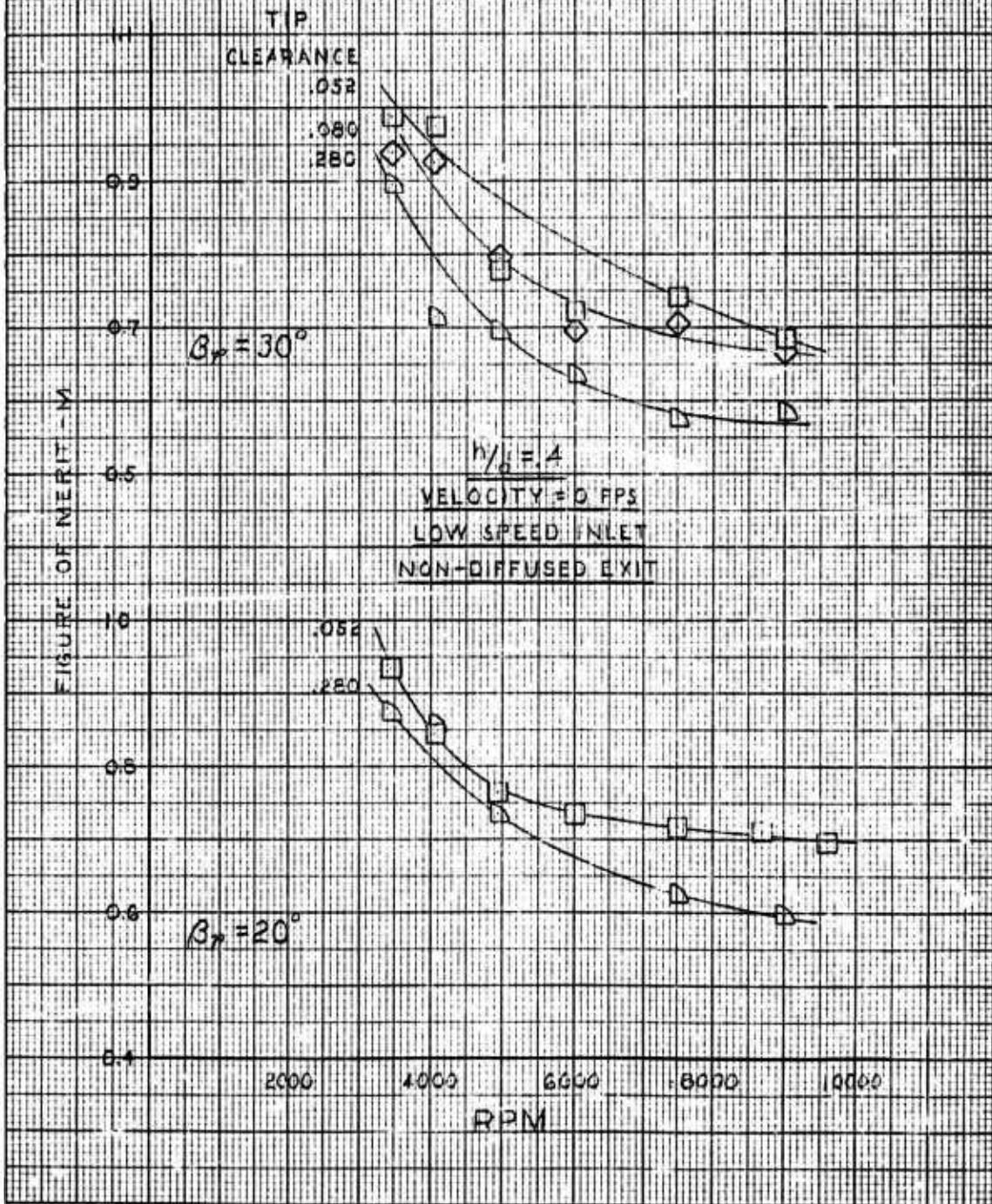
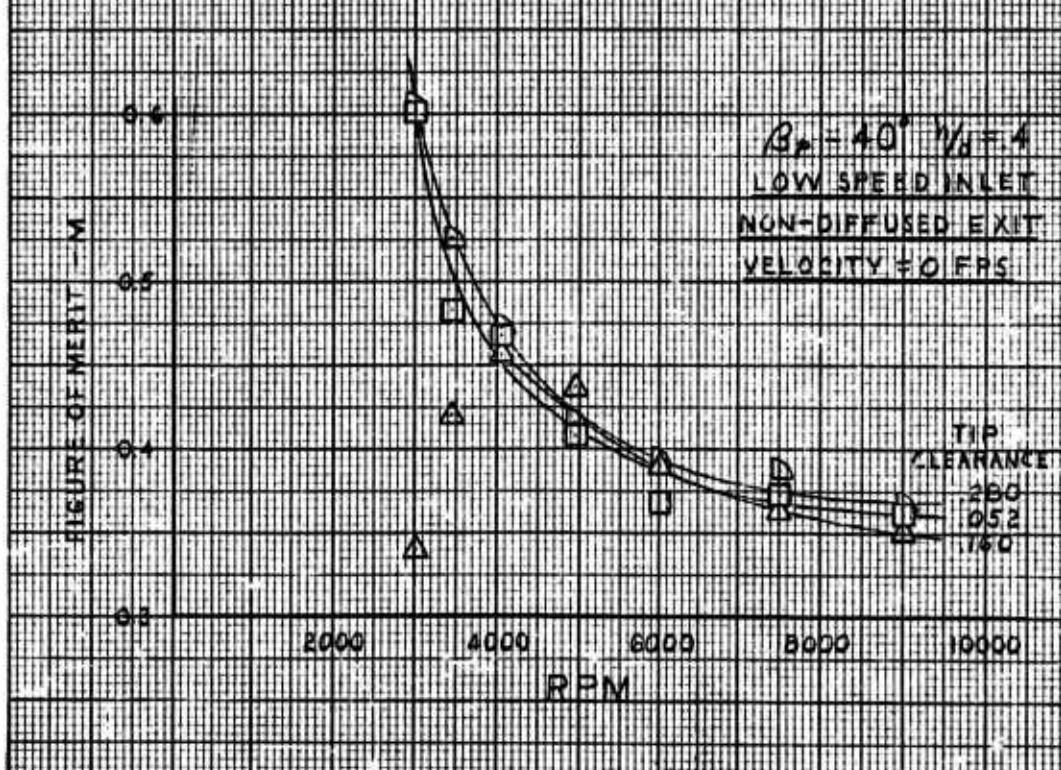
VARIATION OF FIGURE OF MERIT
WITH TIP CLEARANCE

Fig. 9 (cont'd)

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SHROUDED PROPELLER MODEL 213K

VARIATION OF FIGURE OF MERIT
WITH TIP CLEARANCE

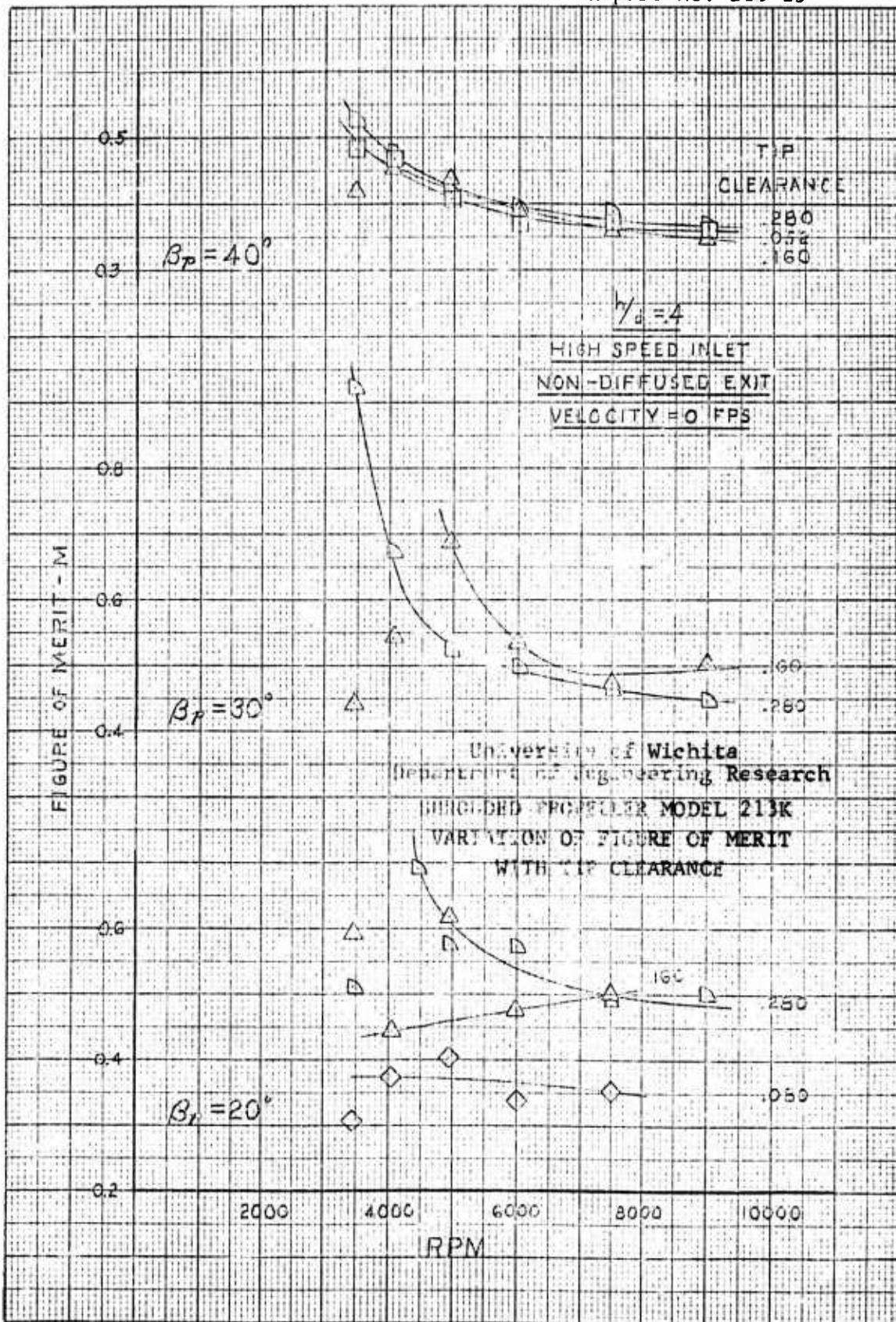
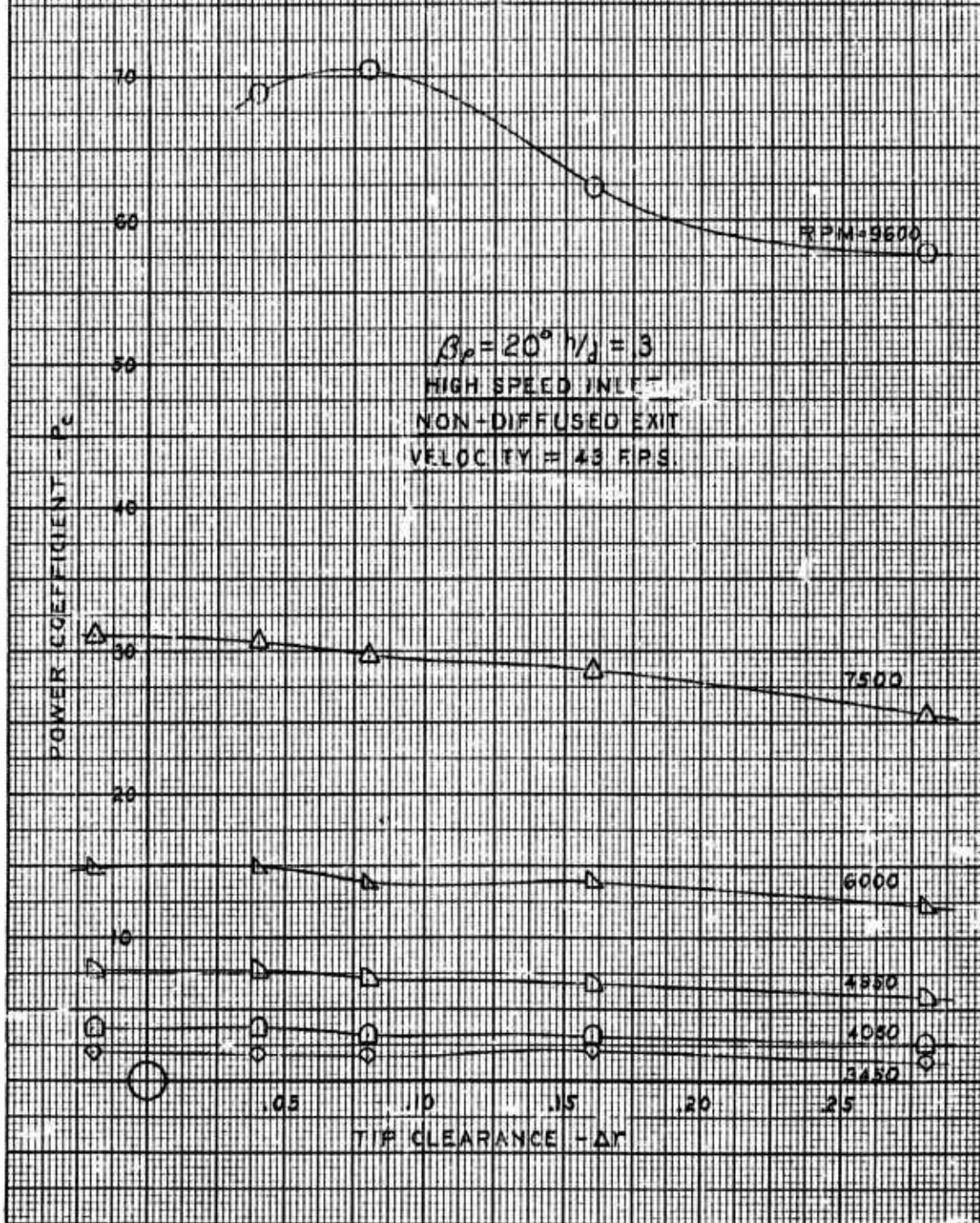


Fig. 9 (concluded)

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SHROUDED PROPELLER MODEL 213K
EFFECT OF TIP CLEARANCE ON FORWARD
FLIGHT POWER COEFFICIENT



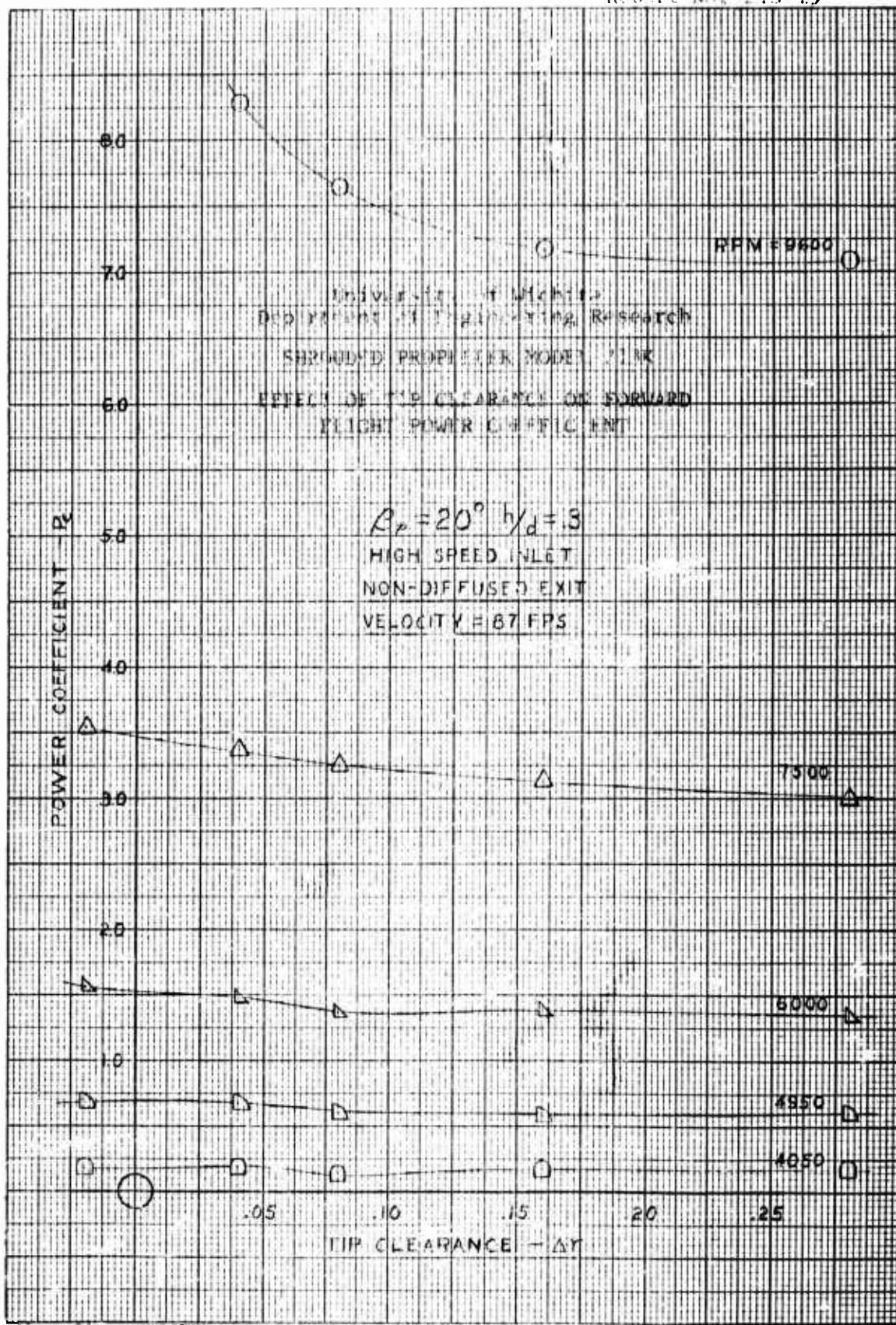
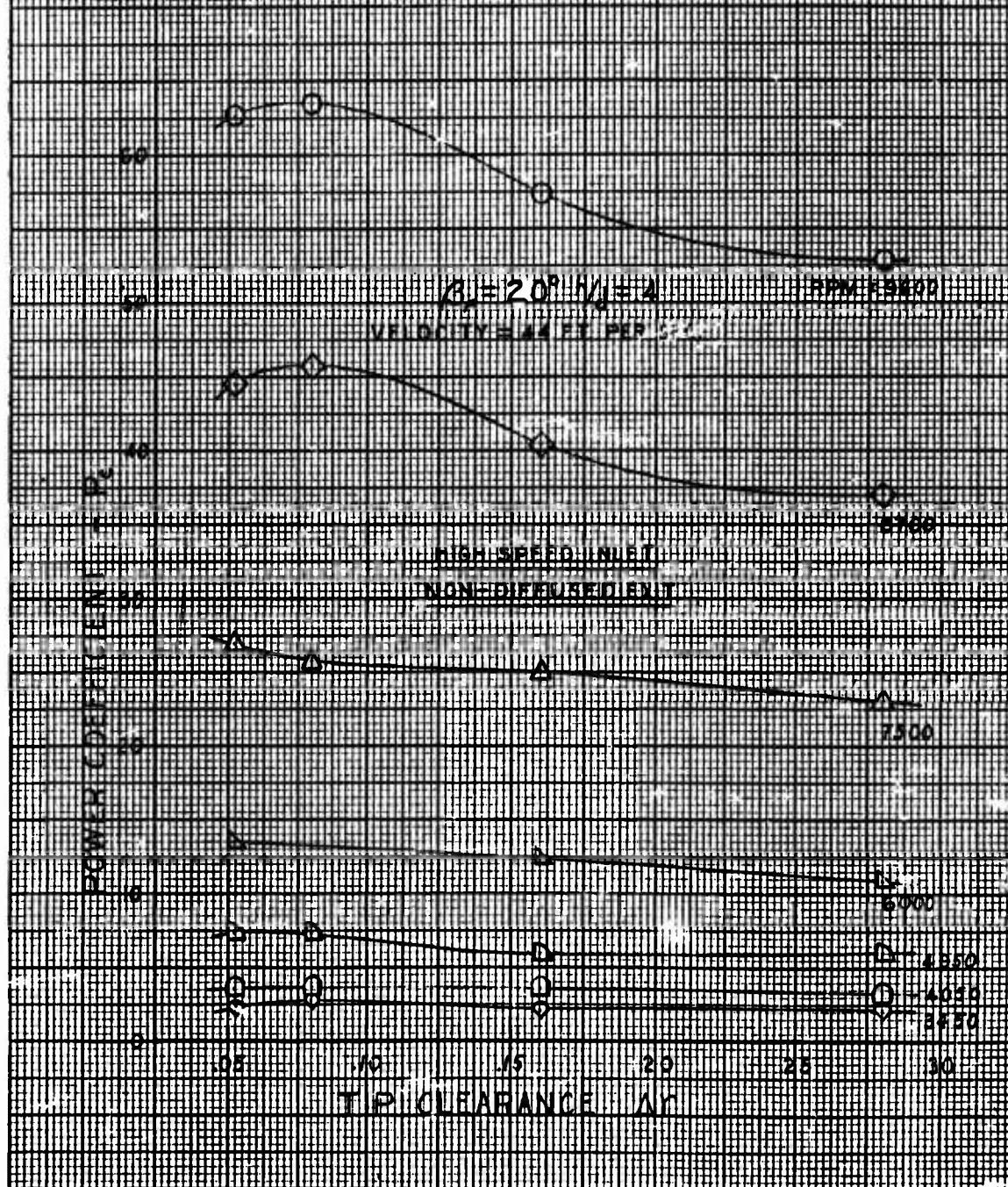


Fig. 10 (cont'd)

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SHROUDED PROPELLER MODEL 213W

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT POWER COEFFICIENT



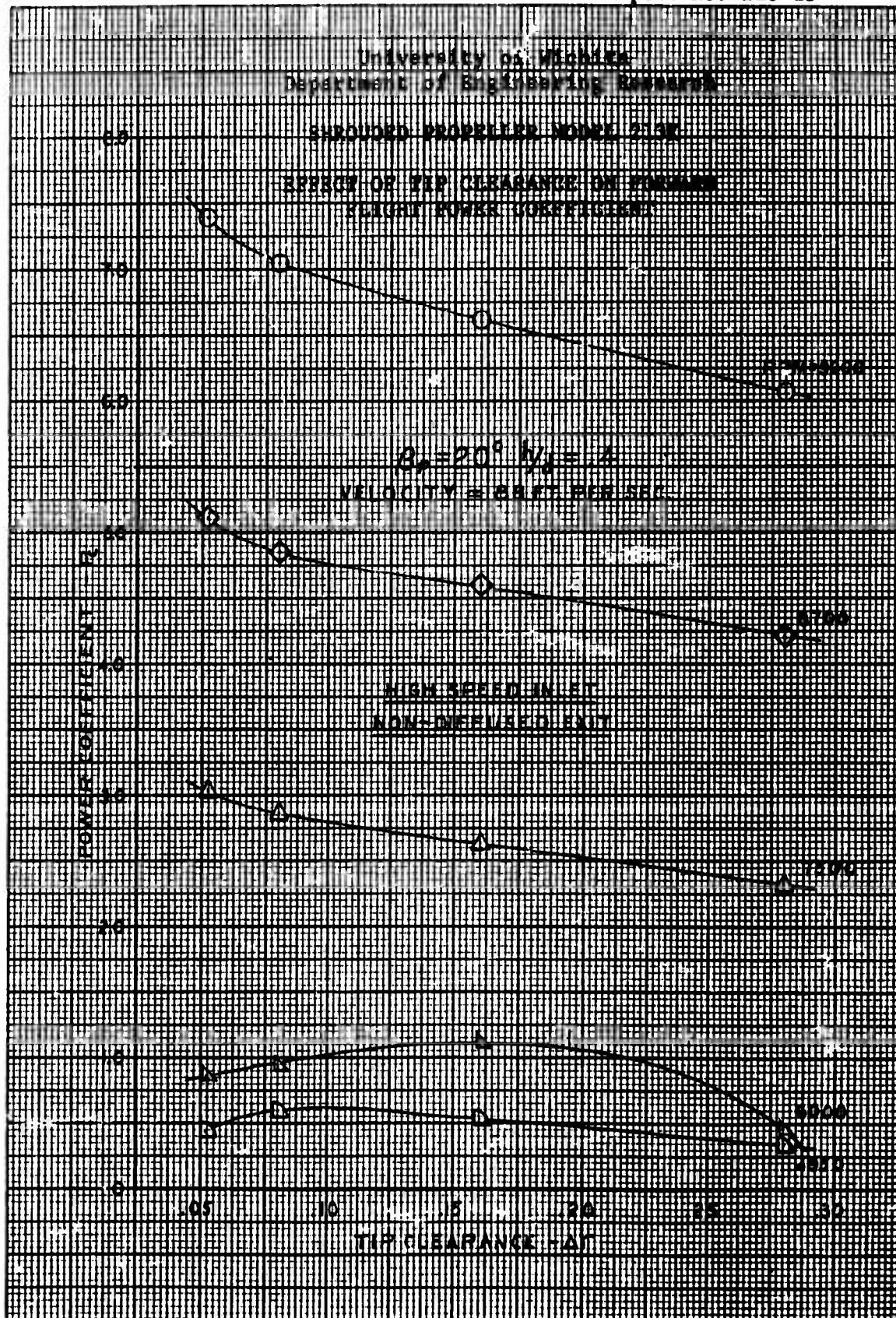
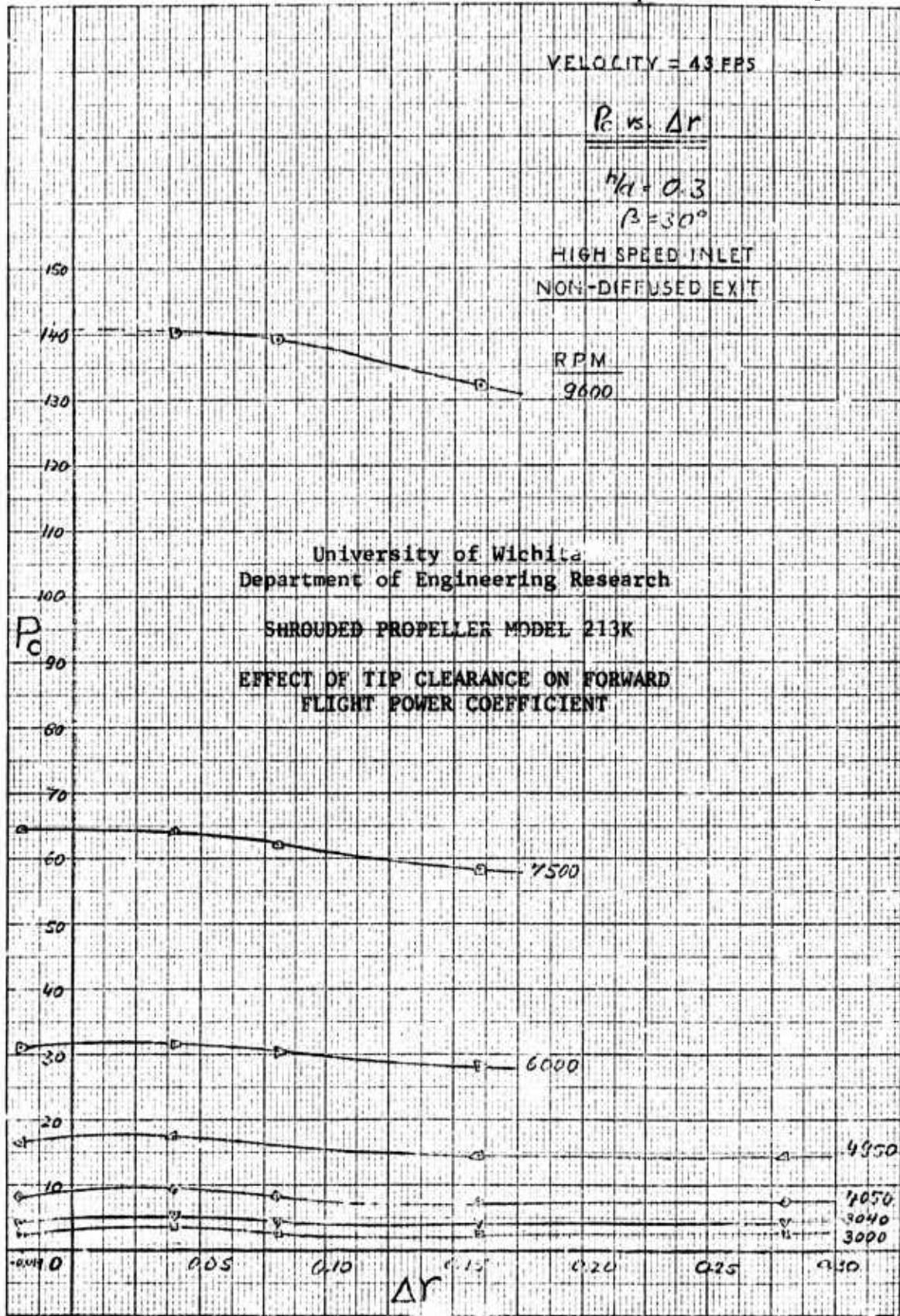


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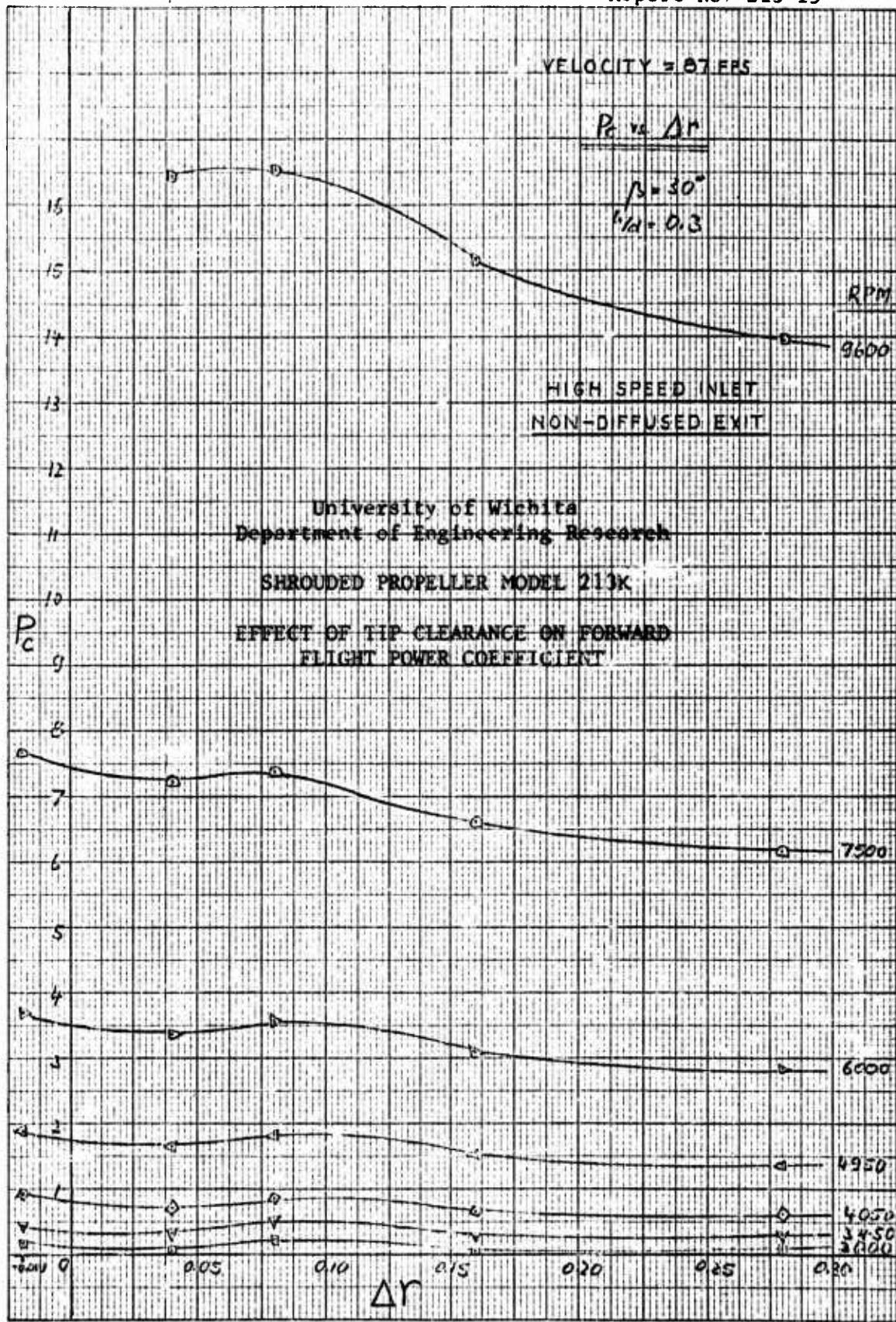
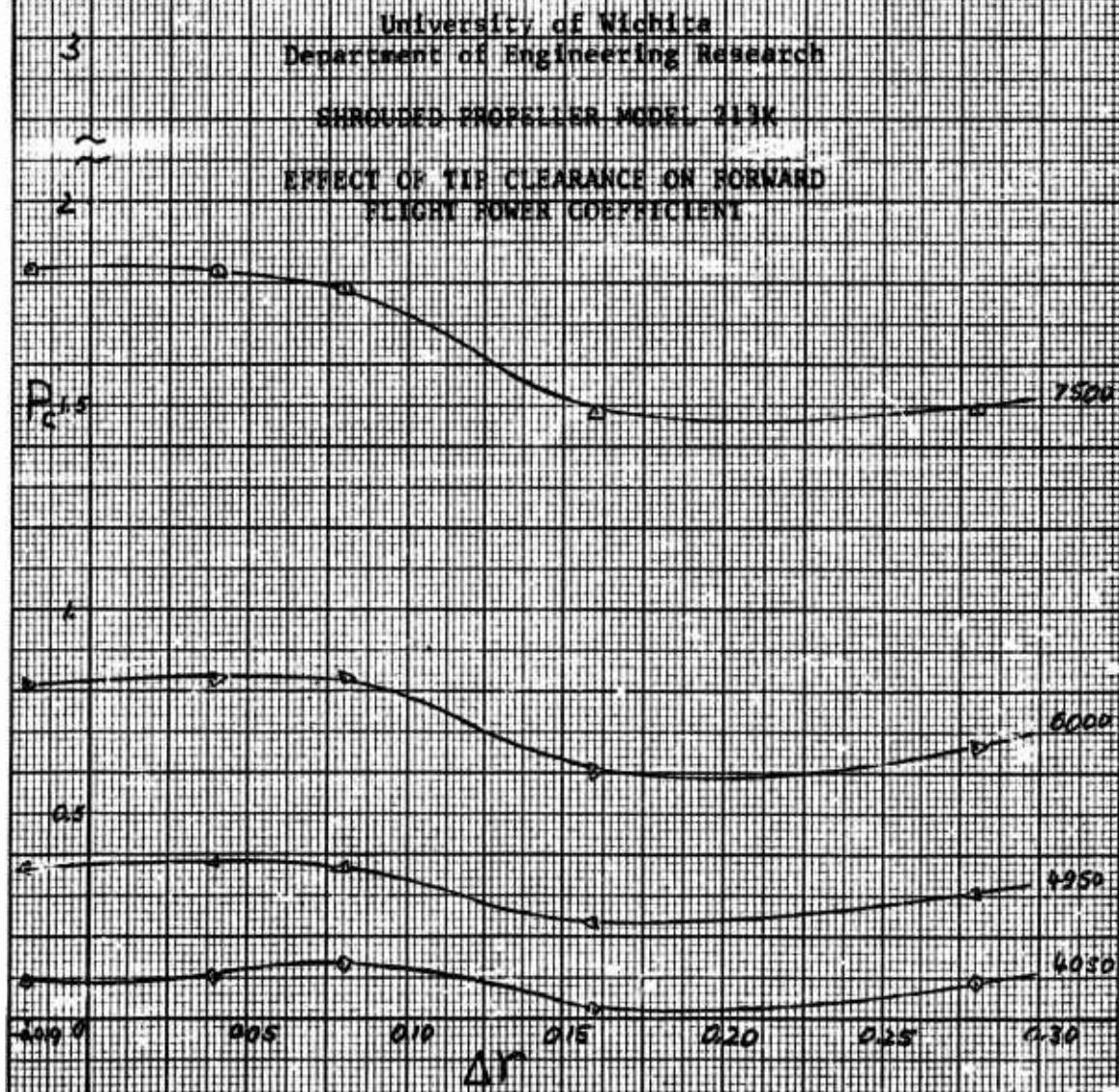
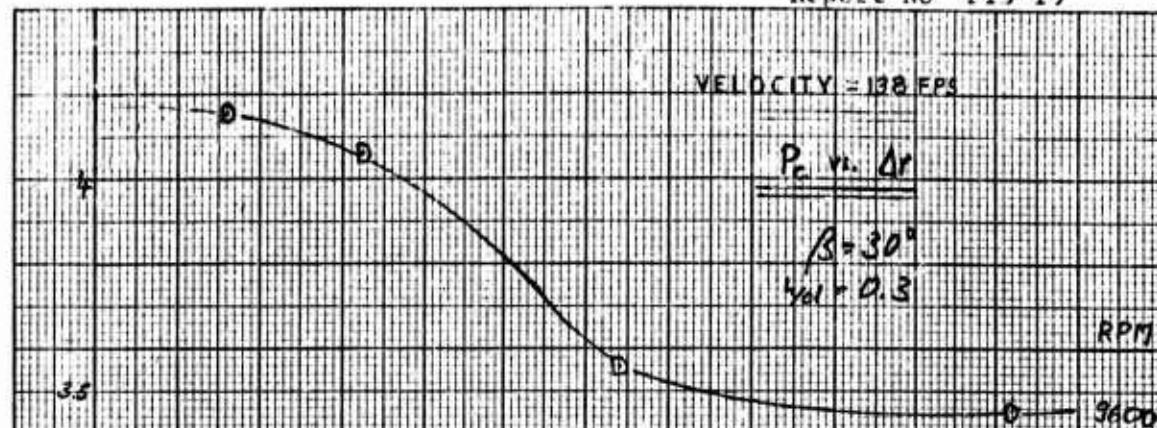


Figure 10 (cont'd)



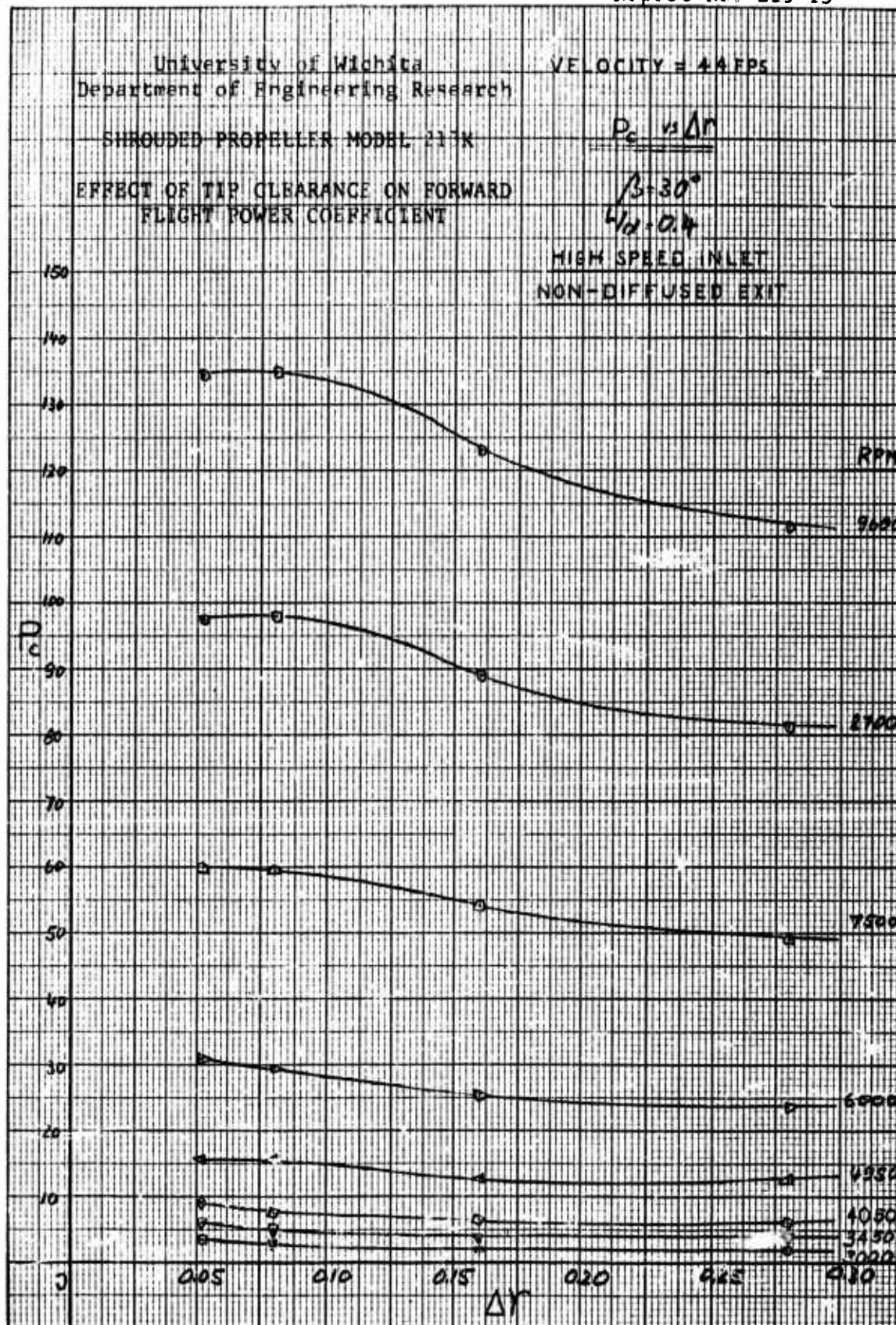
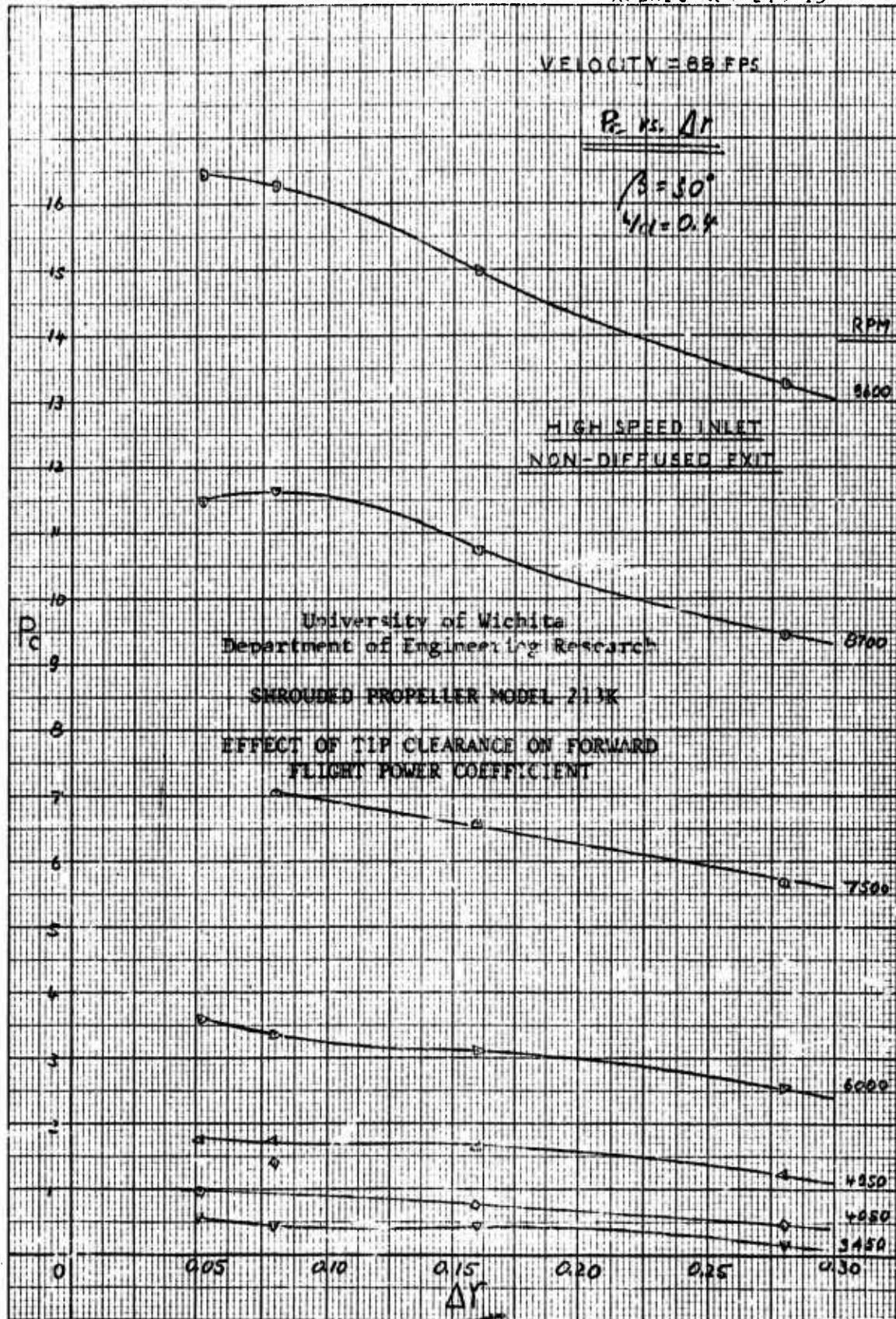


Figure 10 (cont'd)



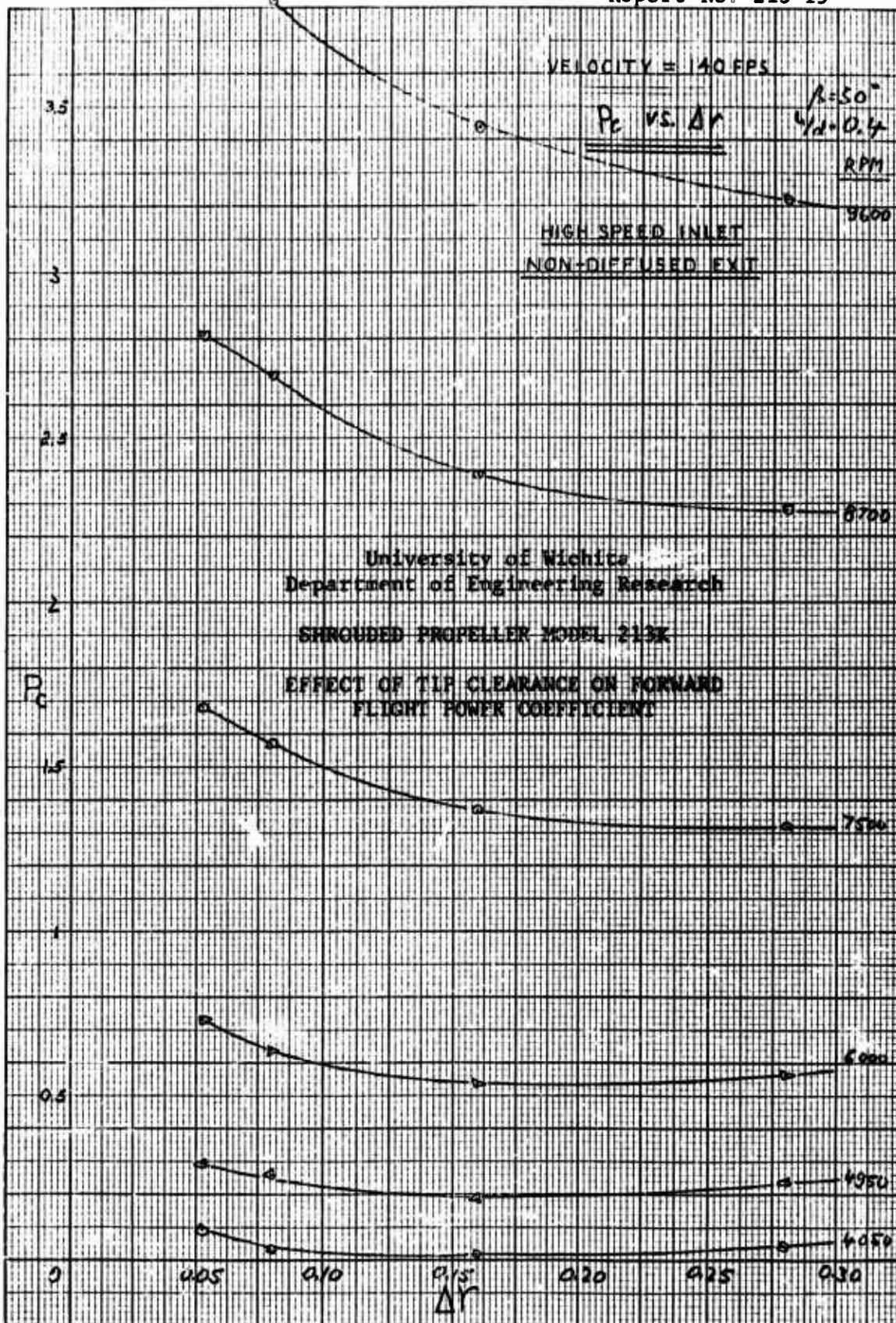
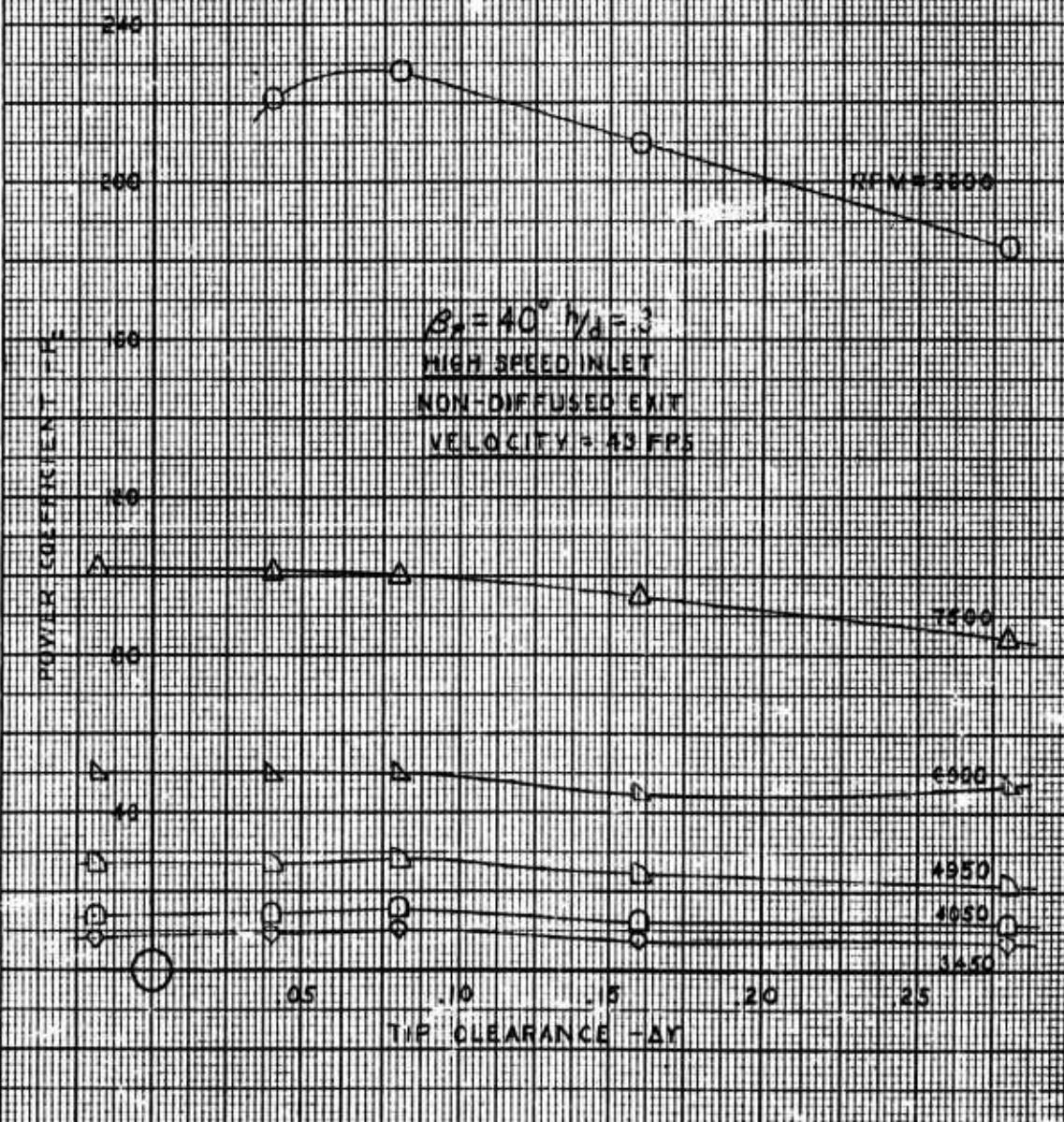


Figure 10 (cont'd)

University of Wichita
Department of Engineering Research

SHROUDED PROPELLER MODEL 213X

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT POWER INEFFICIENCY



University of Wichita
Department of Engineering Research

SHROUDED PROPELLER MODEL 213K

EFFECT OF TIP CLEARANCE ON FORWARD
FLIGHT POWER COEFFICIENT

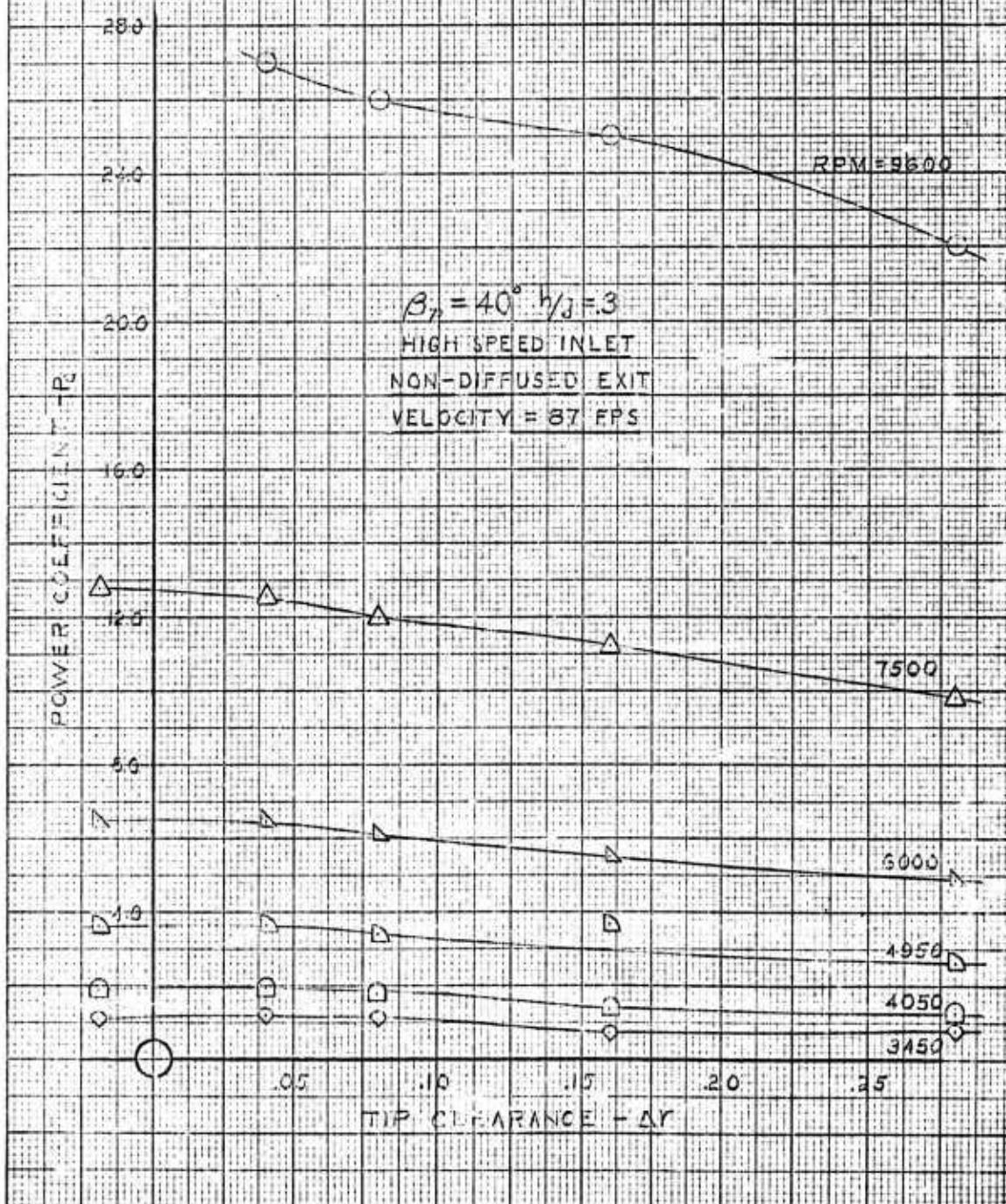
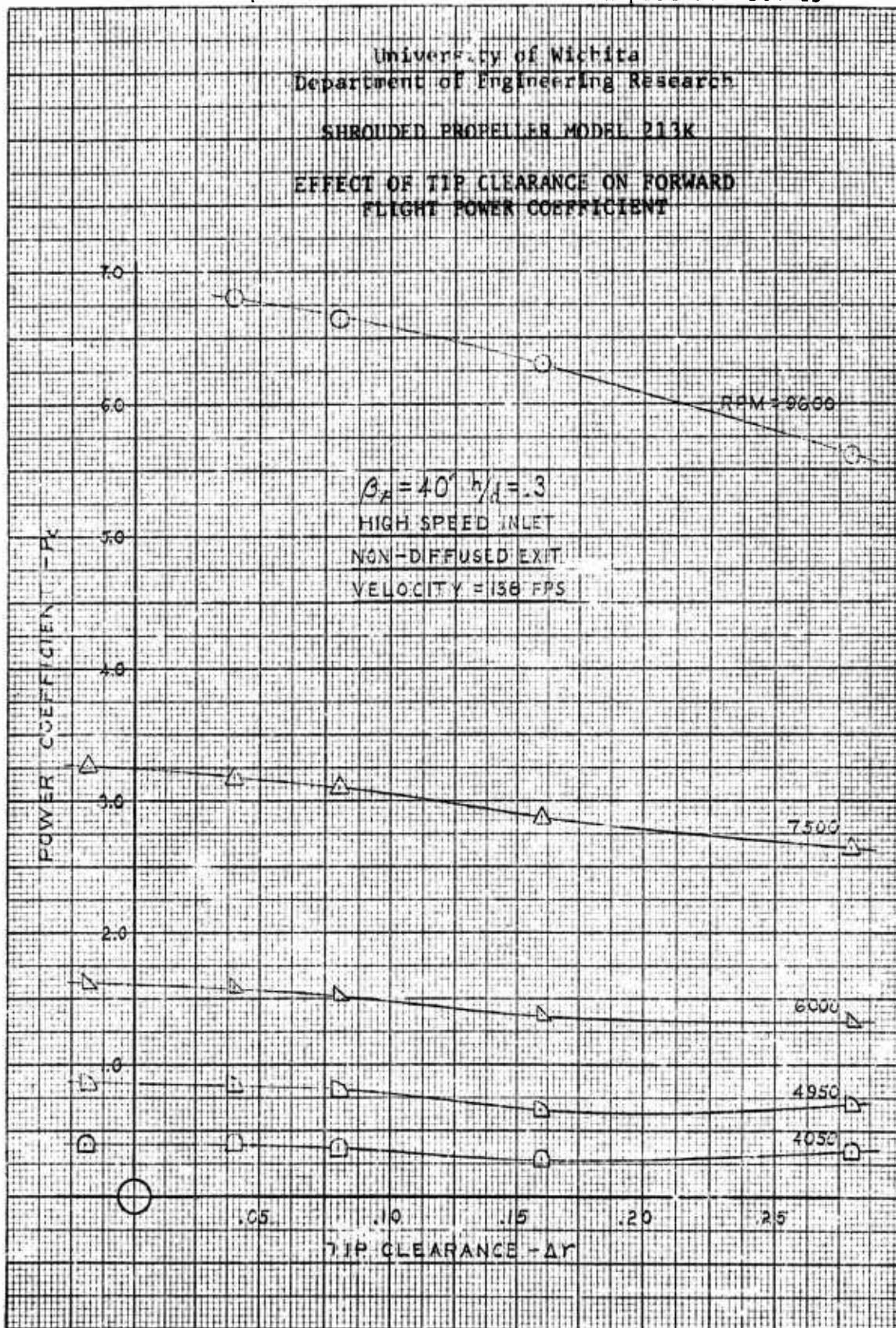


Figure 10 (cont'd)



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Department of Engineering Research

SHROUDED PROPELLER MODEL 213K

EFFECT OF TIP CLEARANCE ON FORWARD
FLIGHT POWER COEFFICIENT

$$\beta_p = 40^\circ \quad V_d = .4$$

HIGH SPEED INLET

NON-DIFFUSED EXIT

VELOCITY = 44 FPS

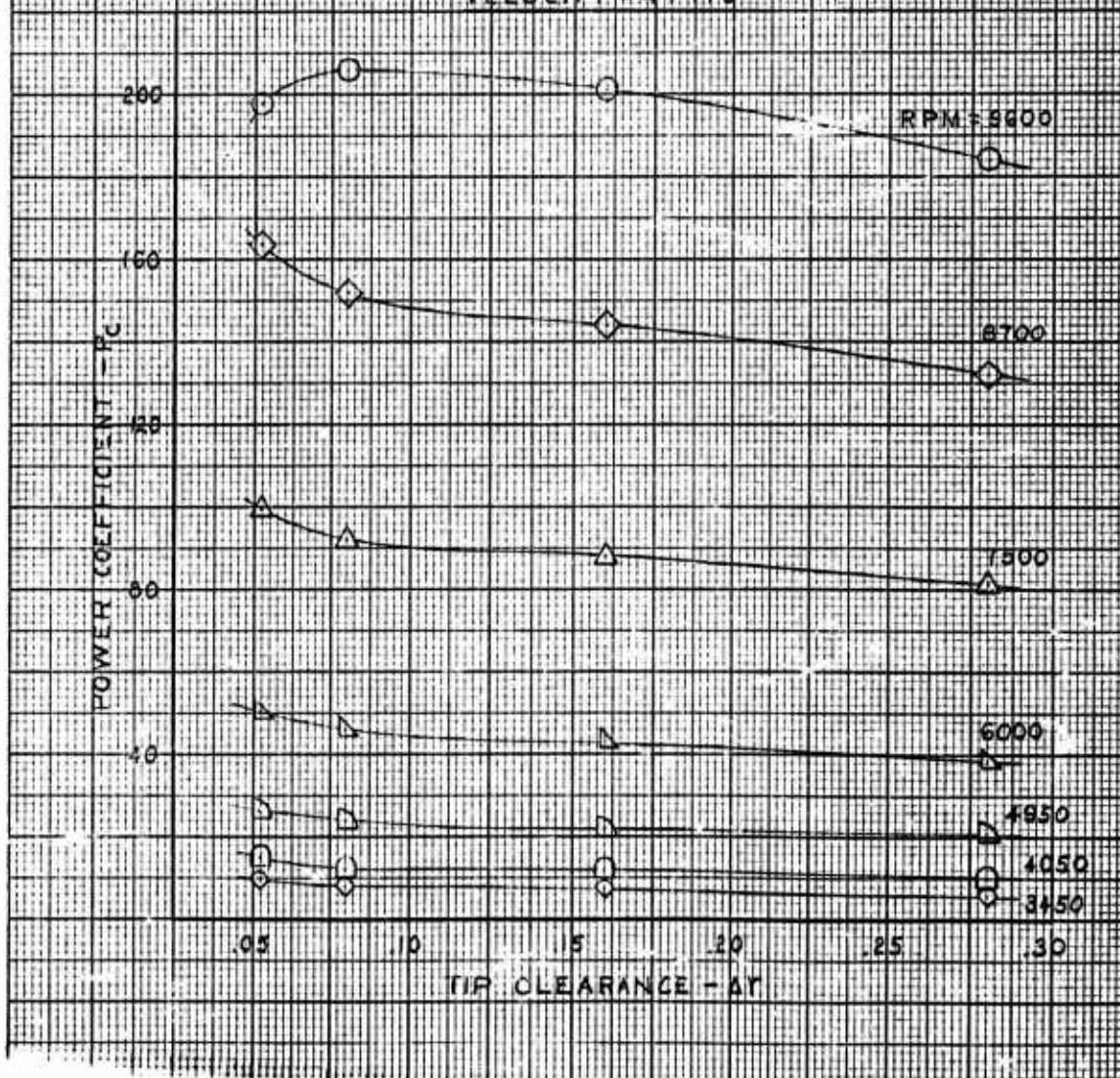
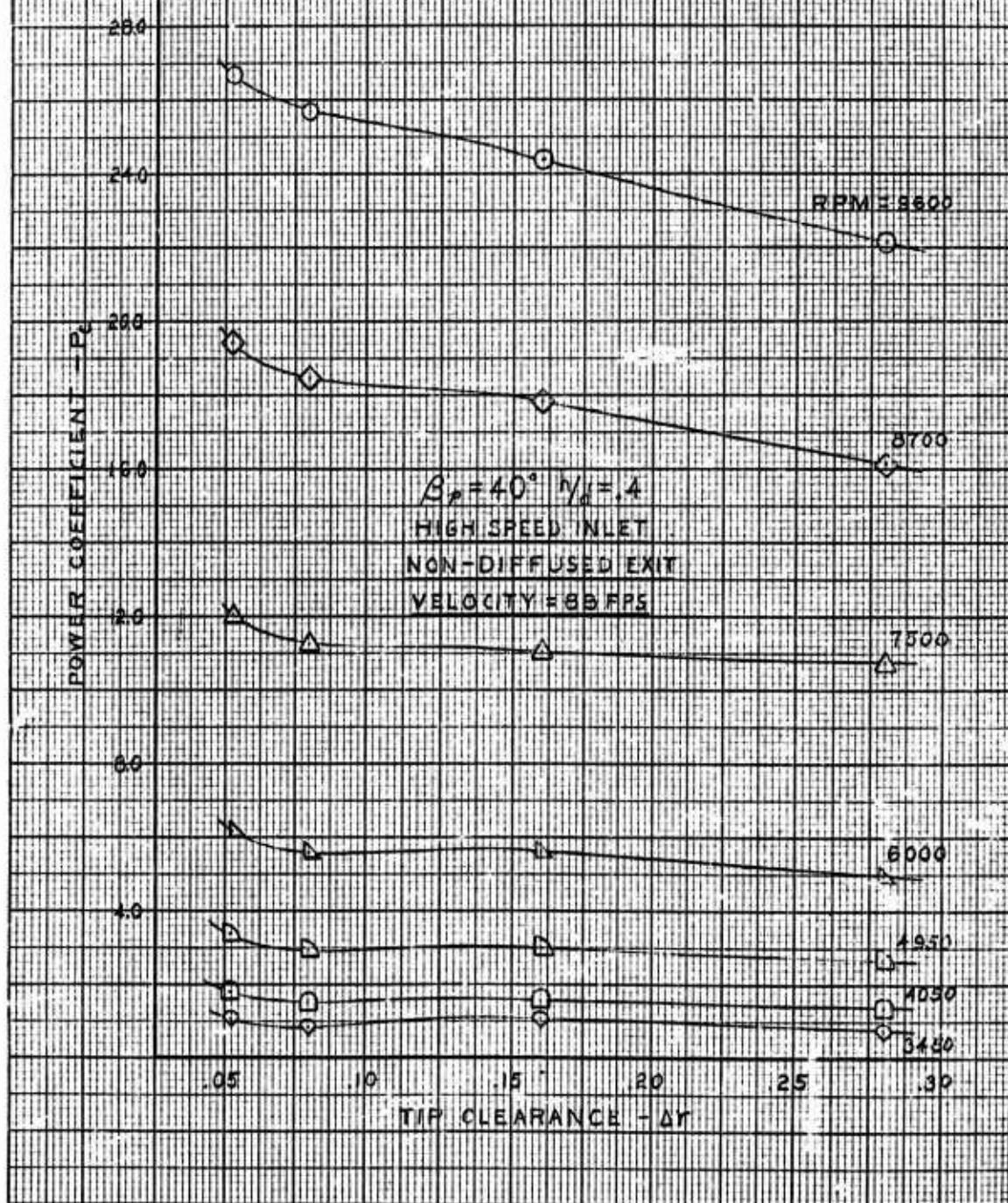


Figure 10 (cont'd)

University of Wichita
Department of Engineering Research

SHROUDED PROPELLER MODEL 213X

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT POWER COEFFICIENT



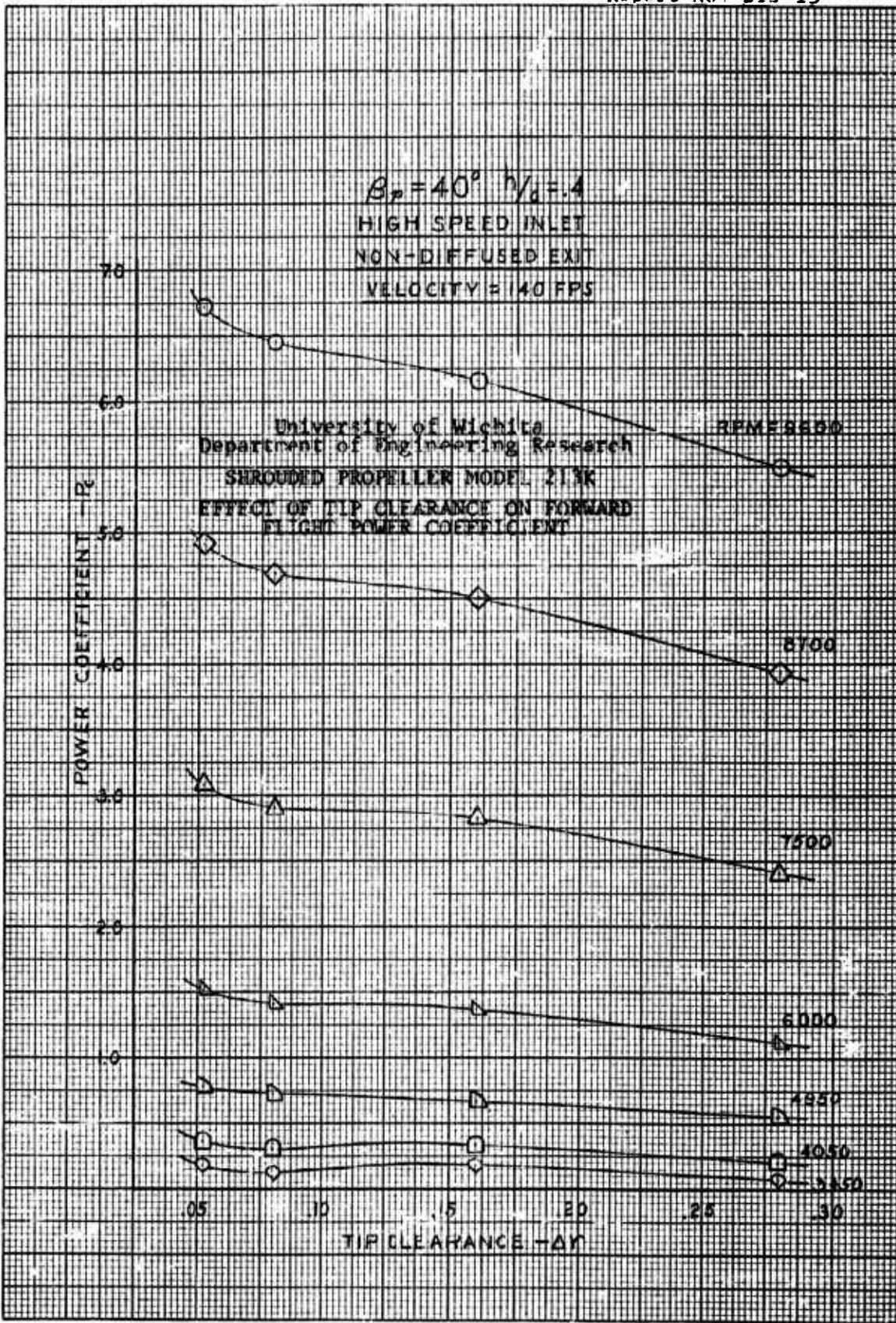
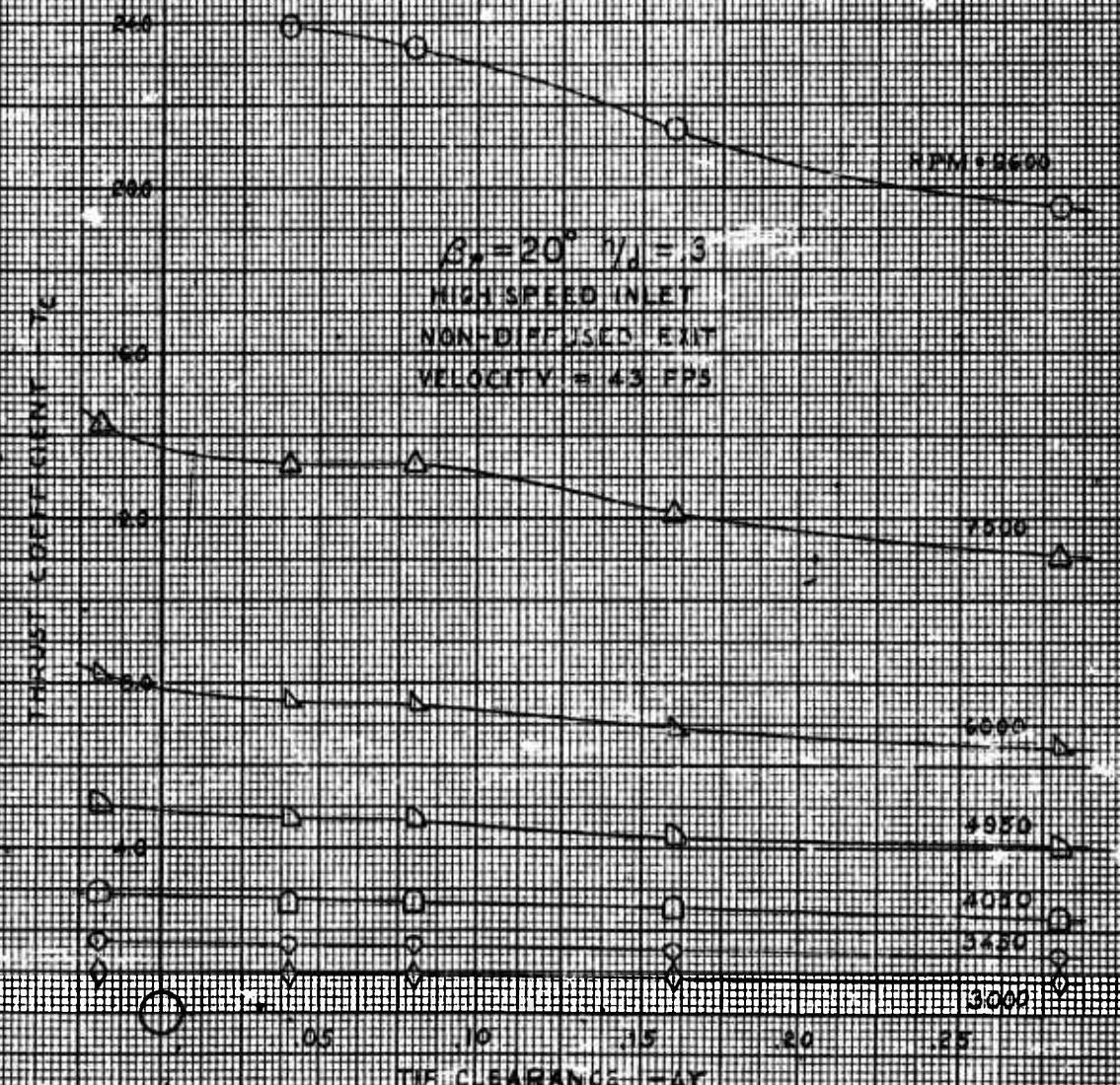


Figure 10 (concluded)

**University of Wichita
Department of Engineering Research**

SHROUDED PROPELLER MODEL 2000

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT TOTAL THRUST COEFFICIENT



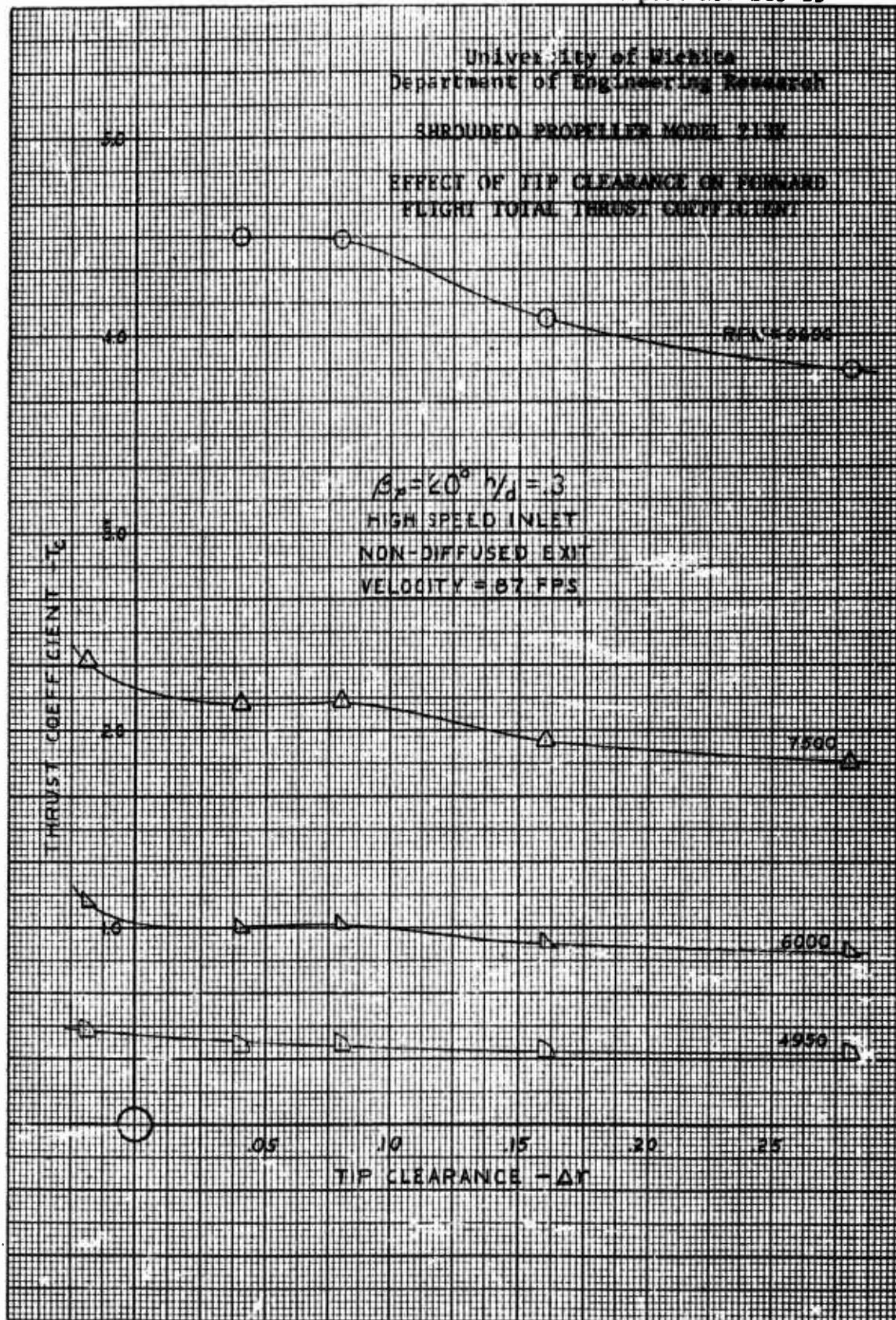
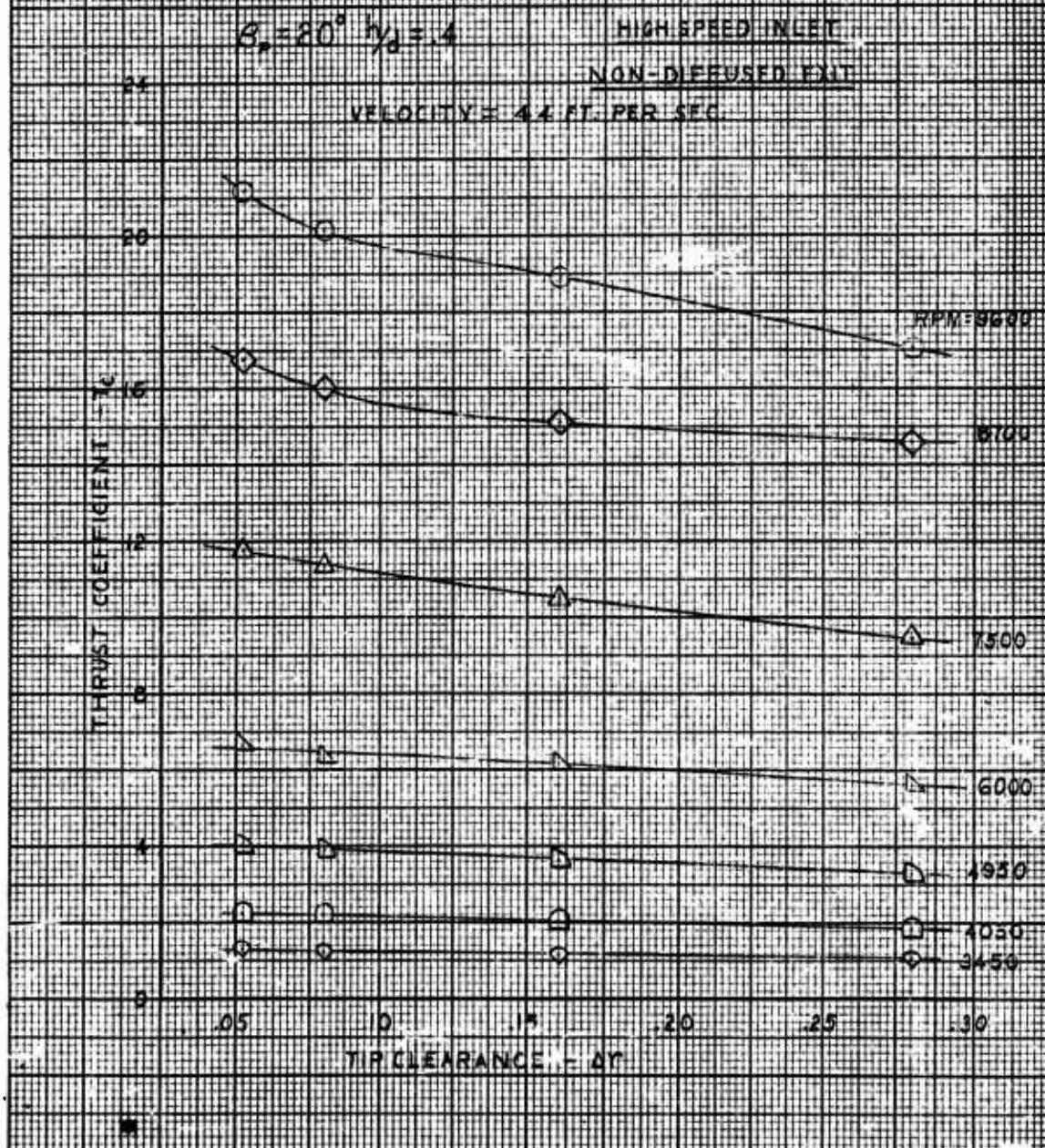


Figure 11 (cont'd)

University of Wichita
Department of Engineering Research

~~SHROUDED PROPELLER MODEL 213X~~

~~EFFECT OF TIP CLEARANCE ON FORWARD
FLIGHT TOTAL THRUST COEFFICIENT~~



UNIVERSITY OF WISCONSIN
DEPARTMENT OF ENGINEERING RESEARCH

SHROUDED PROPELLER MODEL 211V

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT TOTAL THRUST COEFFICIENT

RPM = 9600

6700

$$\beta_p = 20^\circ \quad \frac{V}{d} = 4$$

HIGH SPEED INLET

NON-DIFFUSED EXIT

VELOCITY = 38 FT. PER SEC.

THRUST COEFFICIENT T_C

7500

6000

4950

4500

0.5

1.0

1.5

2.0

2.5

3.0

3.5

4.0

4.5

5.0

5.5

6.0

6.5

7.0

7.5

8.0

8.5

9.0

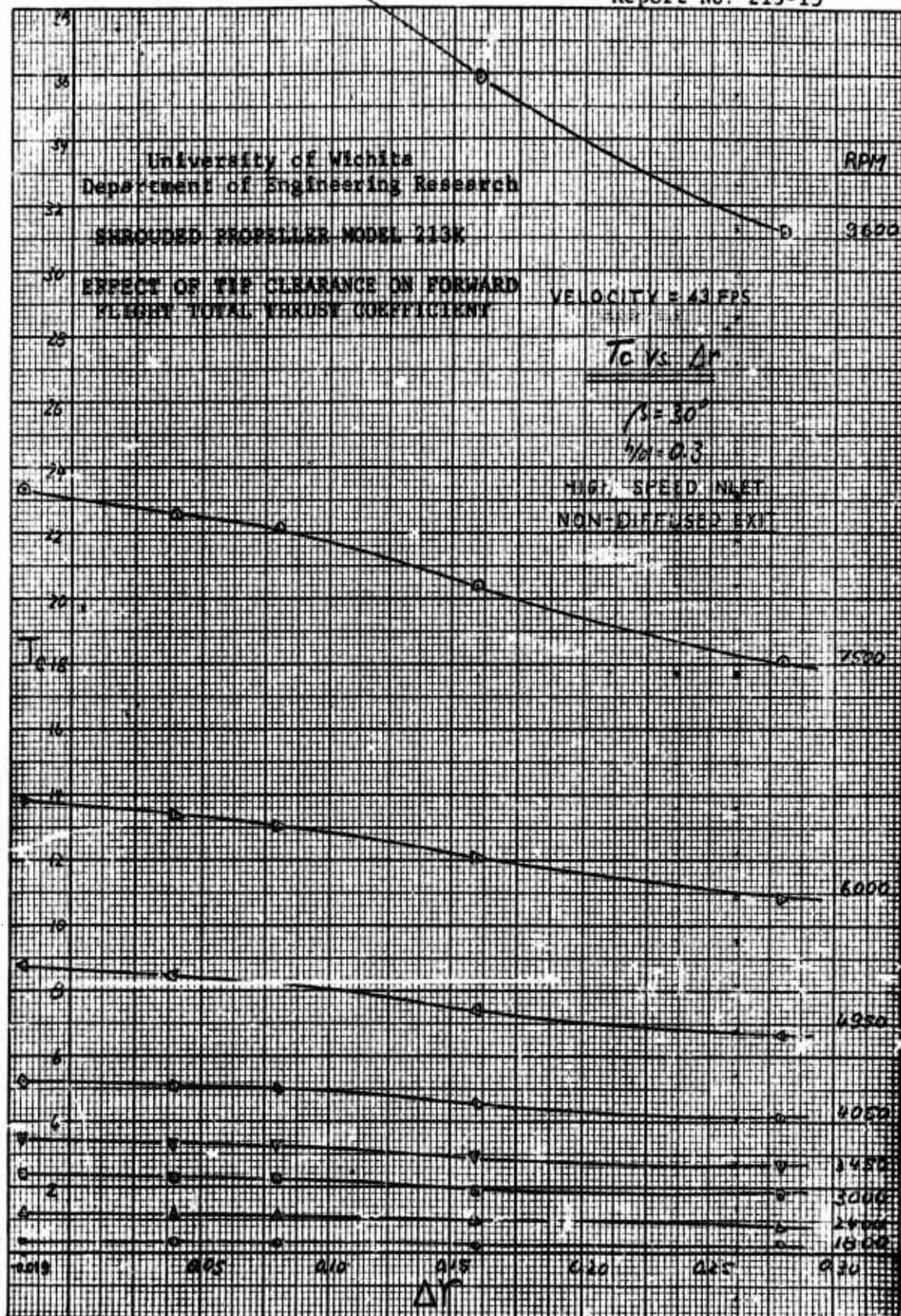
9.5

10.0

TIP CLEARANCE - IN

46

Figure 11 .cont'd)



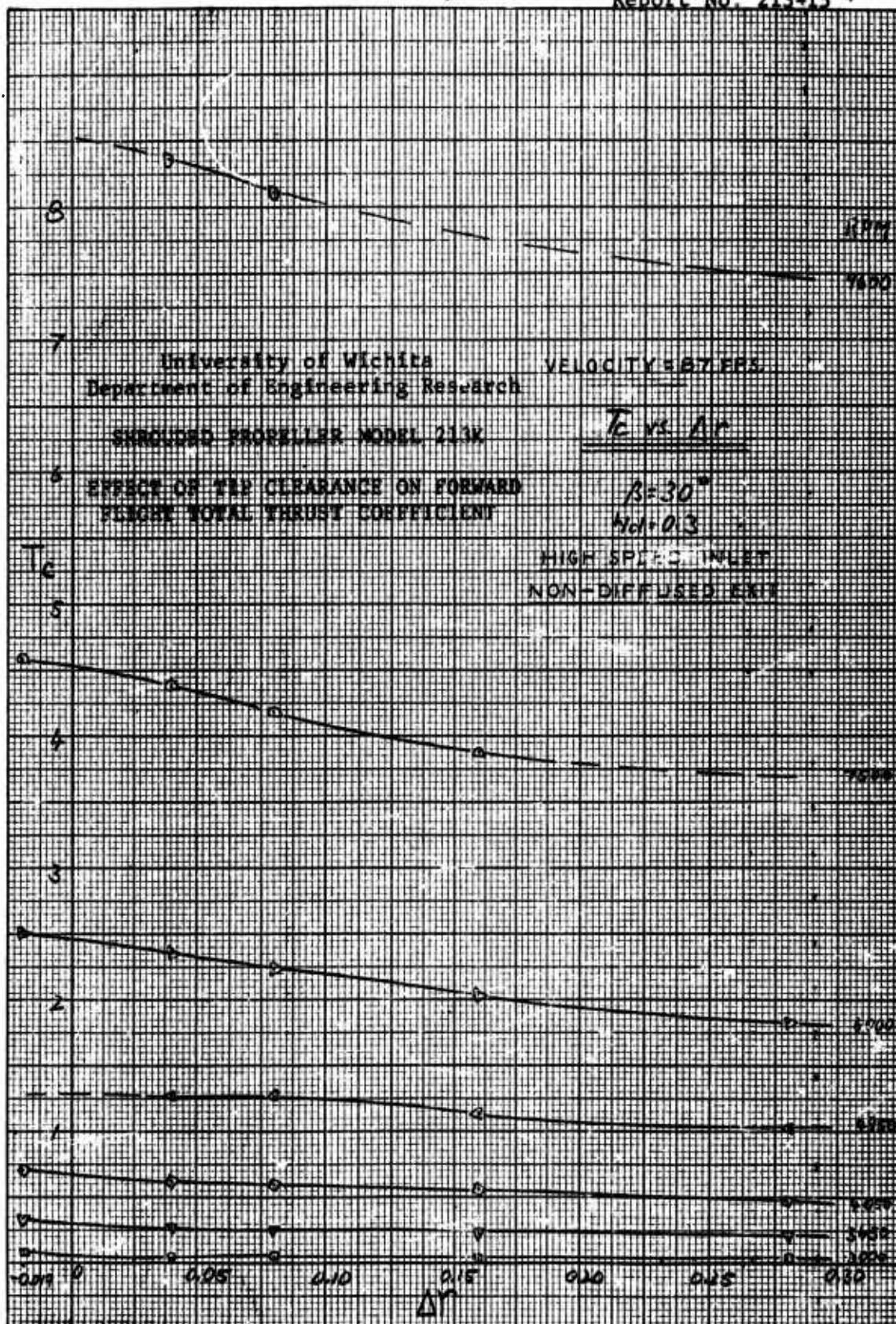
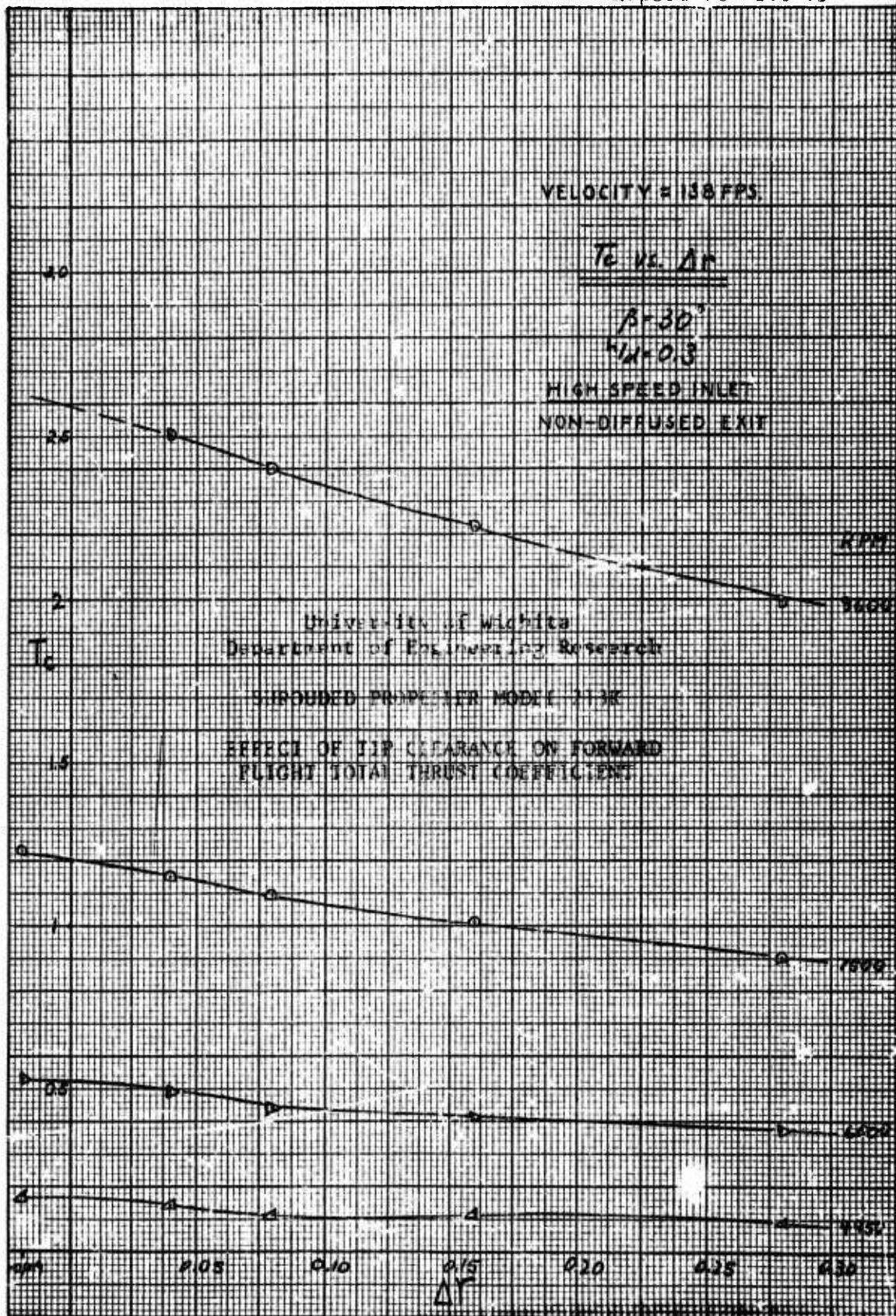


Figure 11 (cont'd)



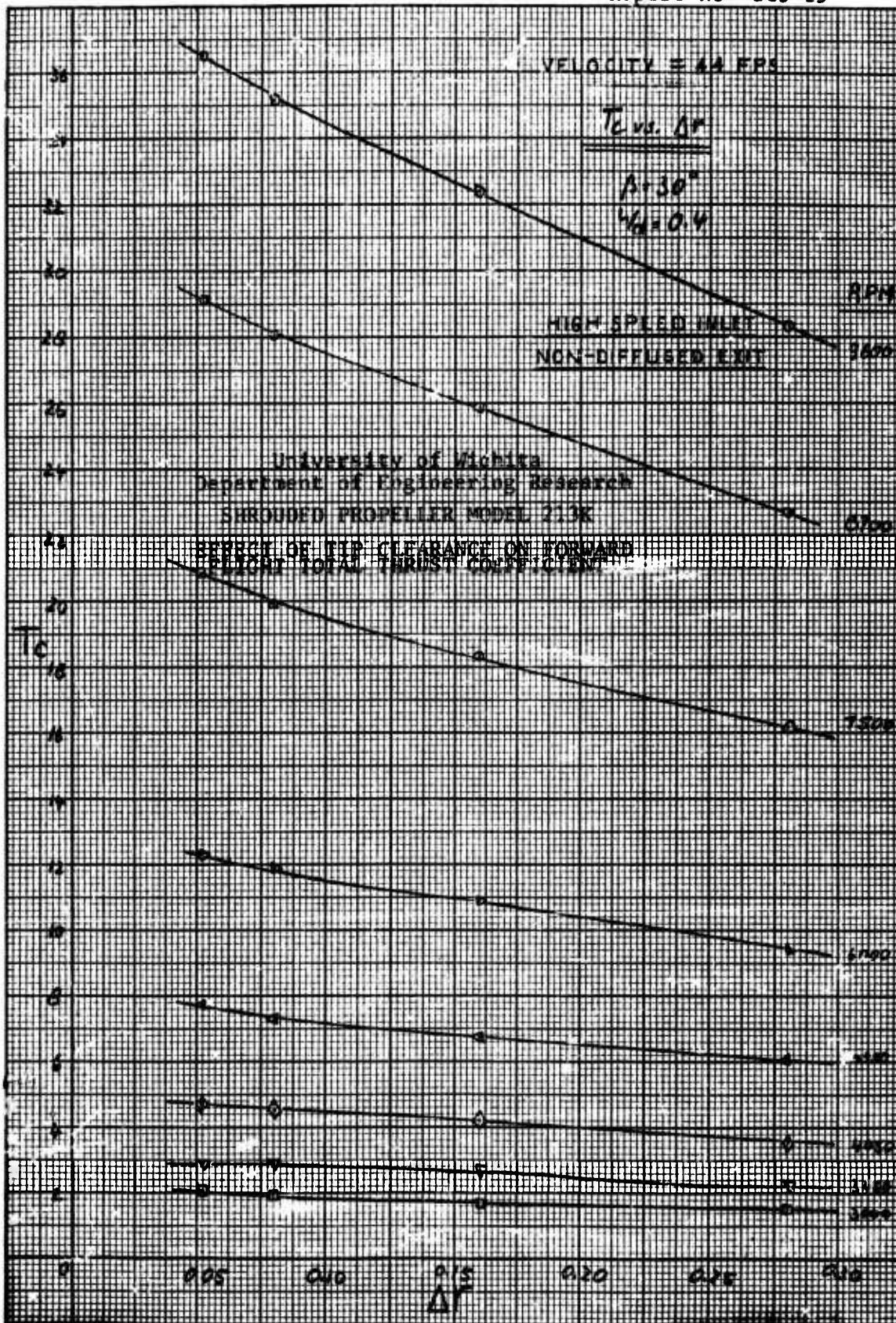
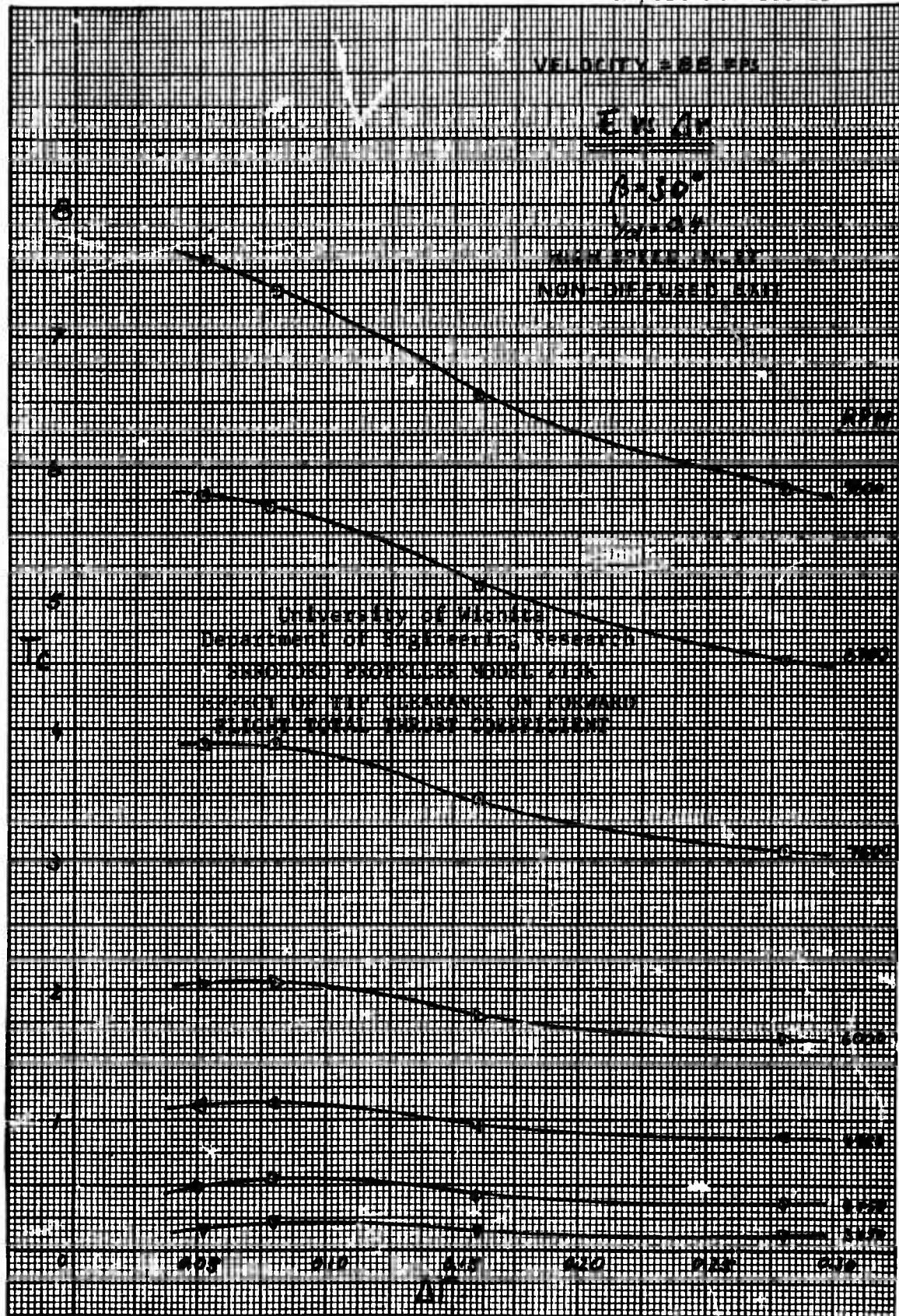


Figure 11 (cont'd)



51

Figure 11 (cont'd)

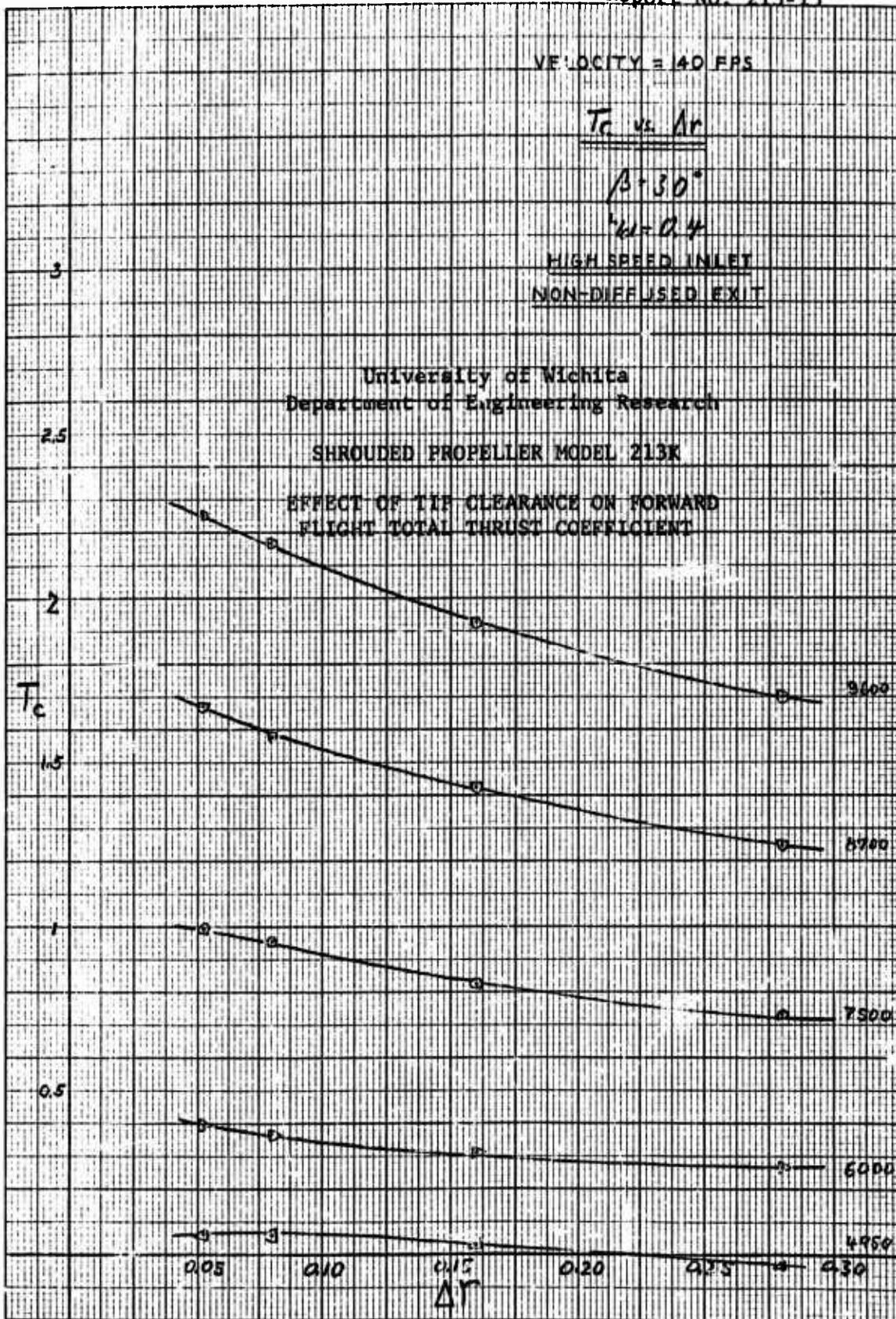
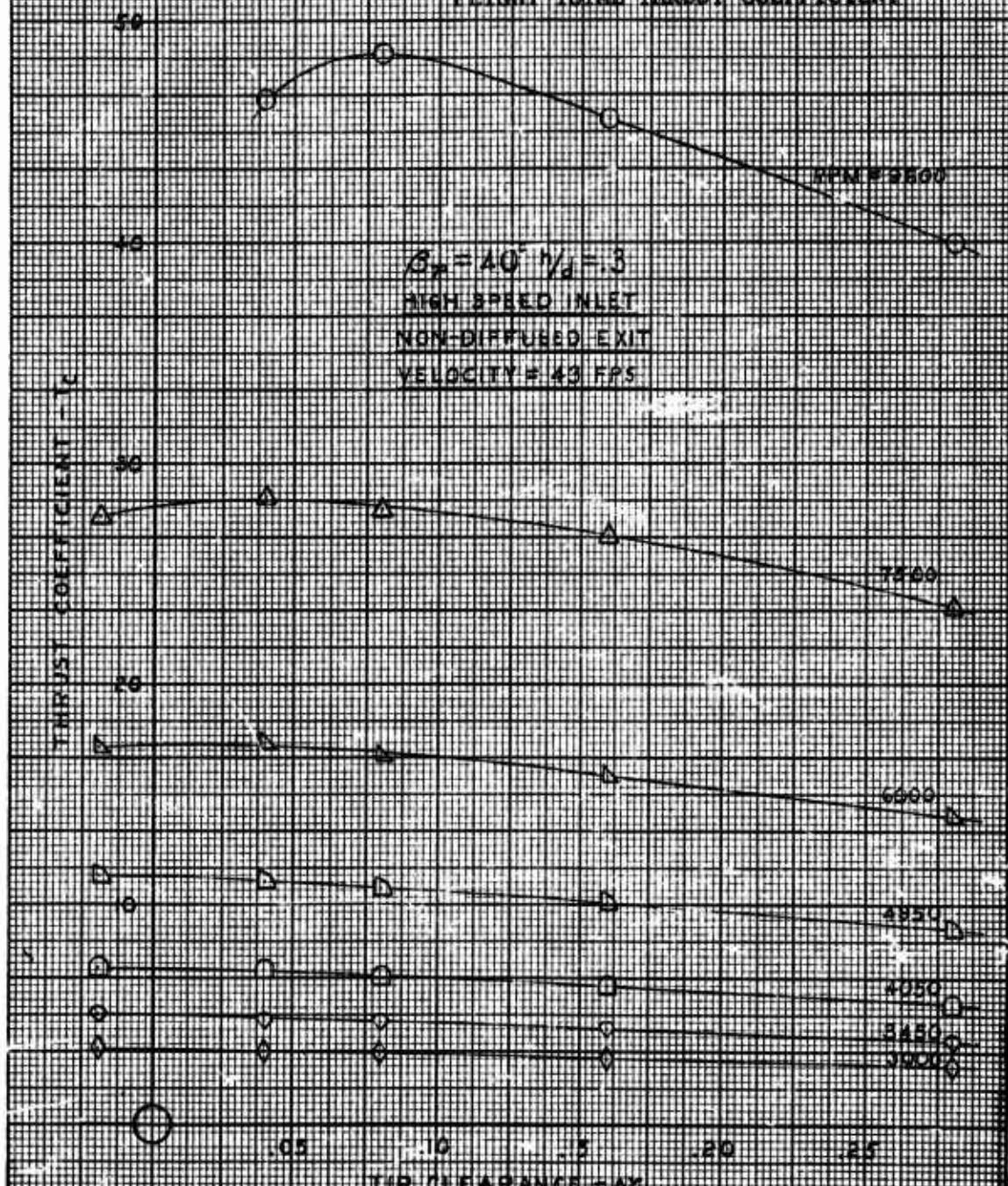


Figure 11 (cont'd)

University of Michigan
Department of Engineering Research
SHROUDED PROPELLER MODEL P13K

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT TOTAL THRUST COEFFICIENT



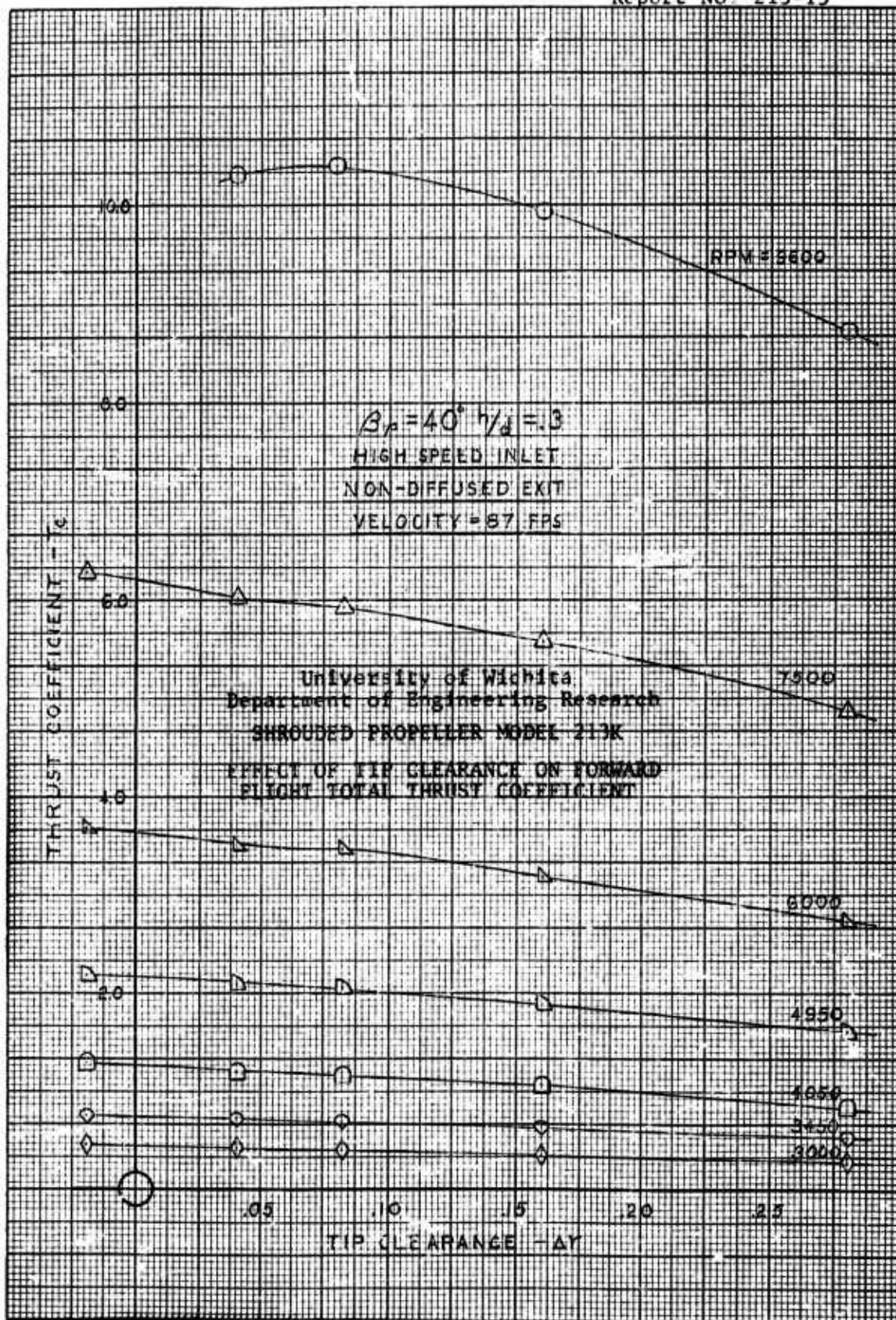
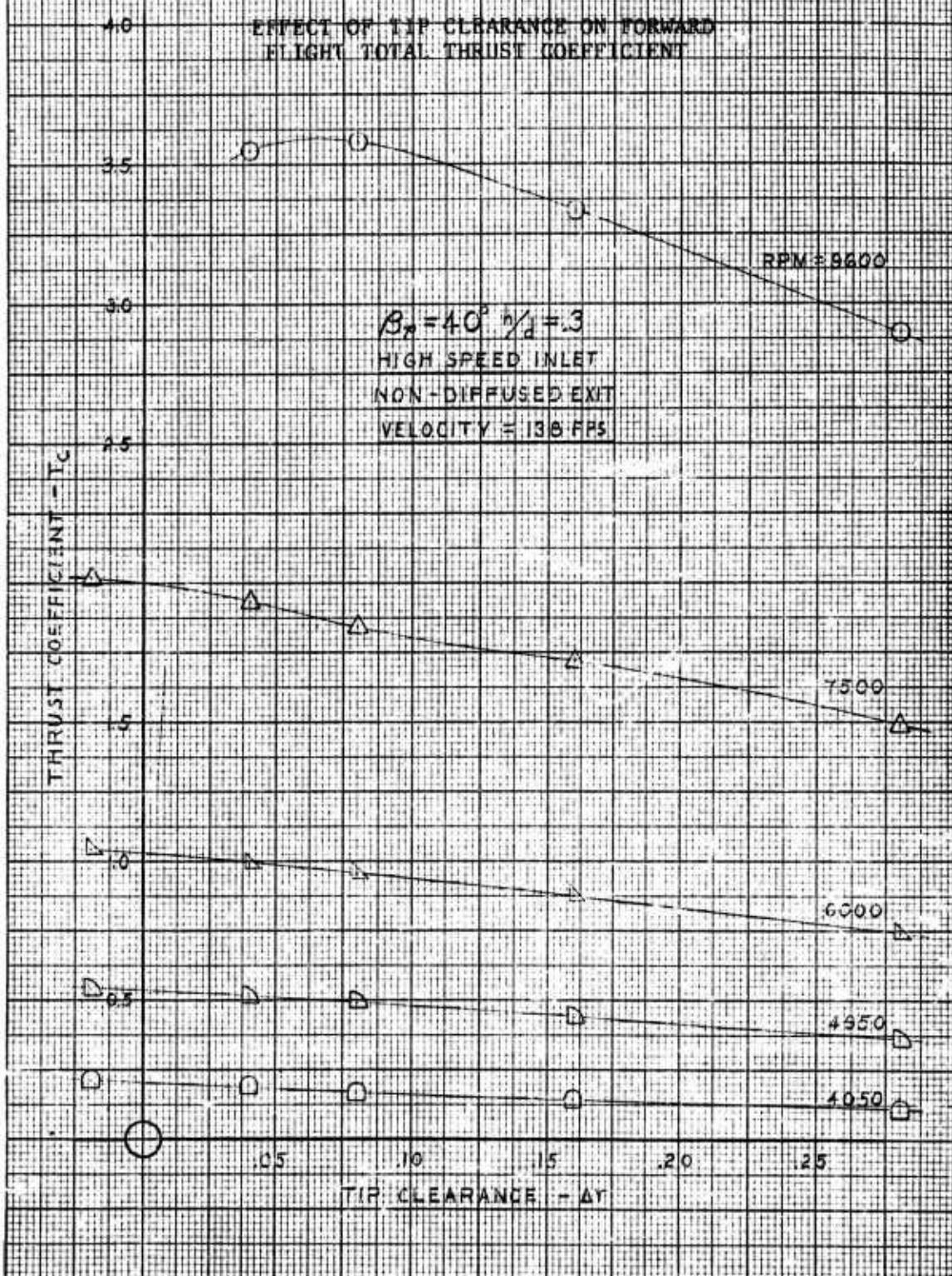


Figure 11 (cont'd)

University of Wichita
Department of Engineering Research

SHROUDED PROPELLER MODEL 213K



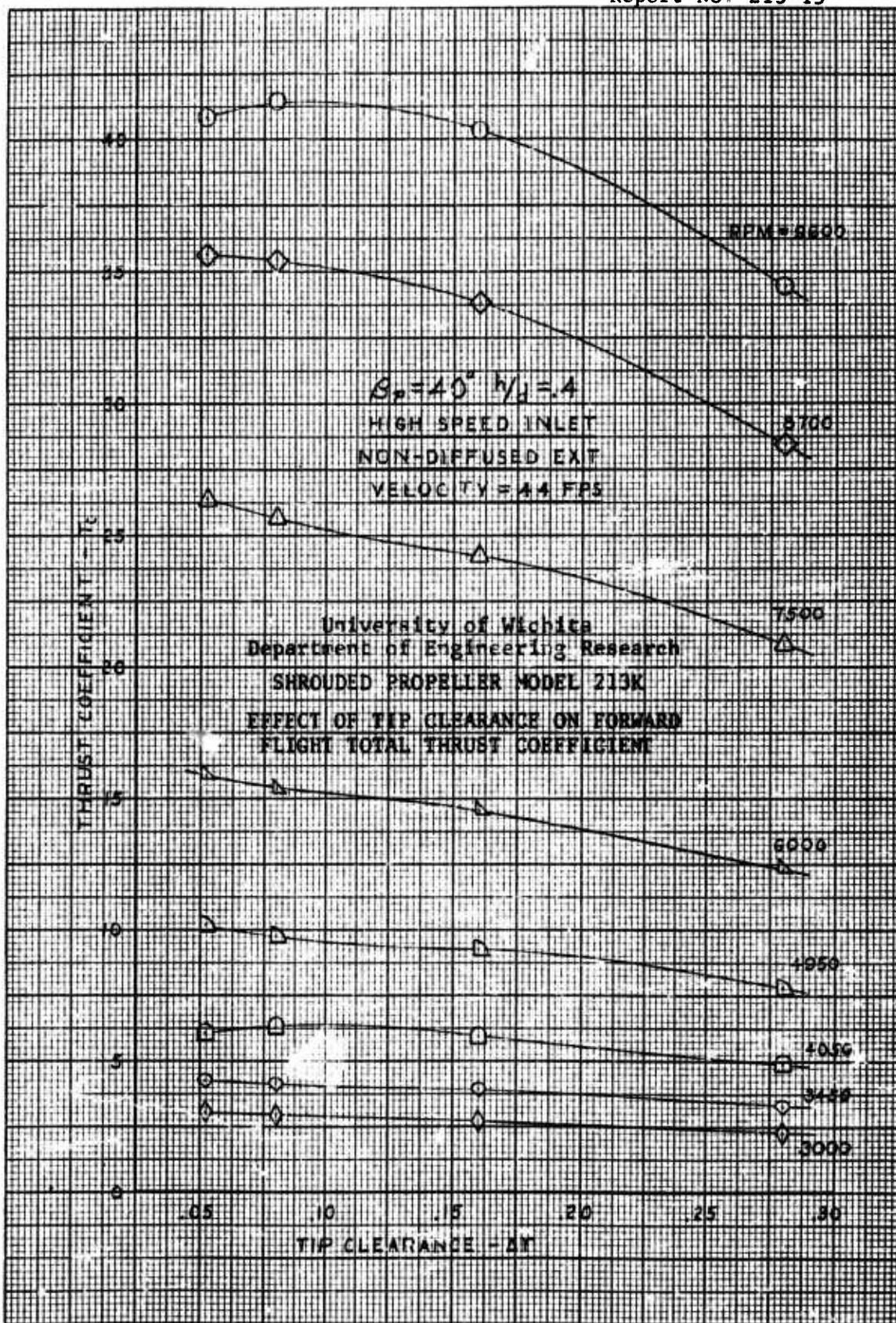
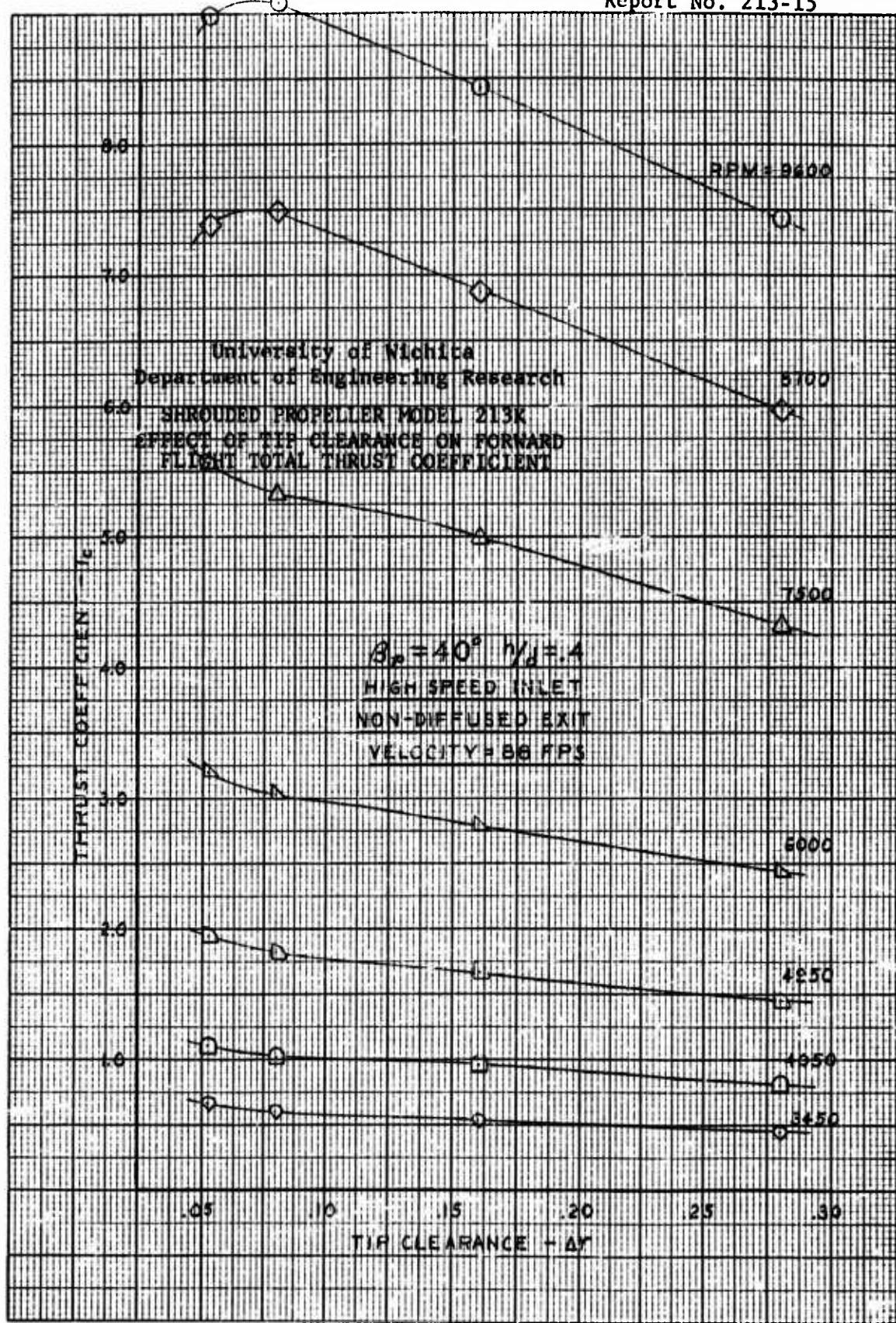


Figure 11 (cont'd)



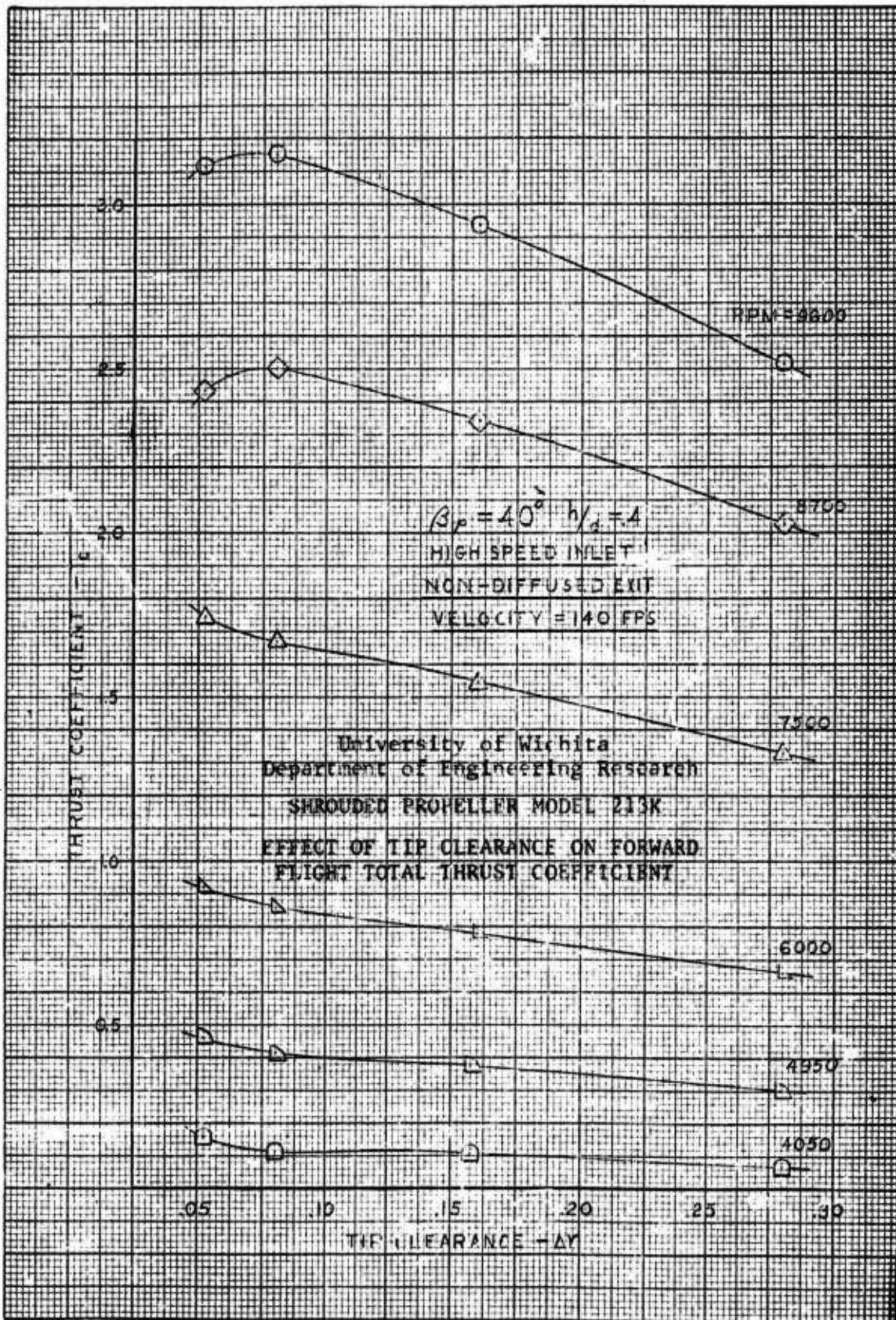
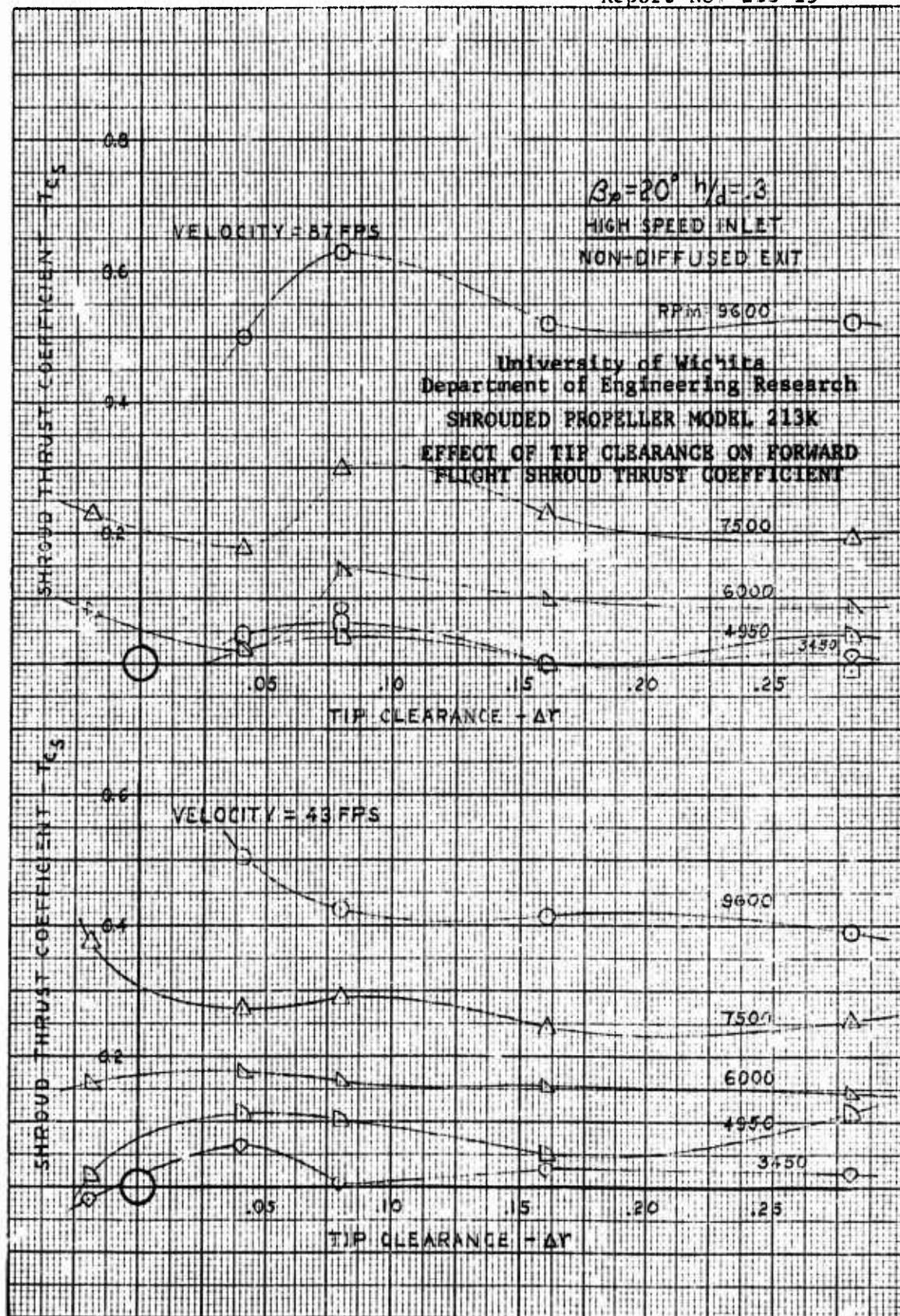


Figure 11 (concluded)



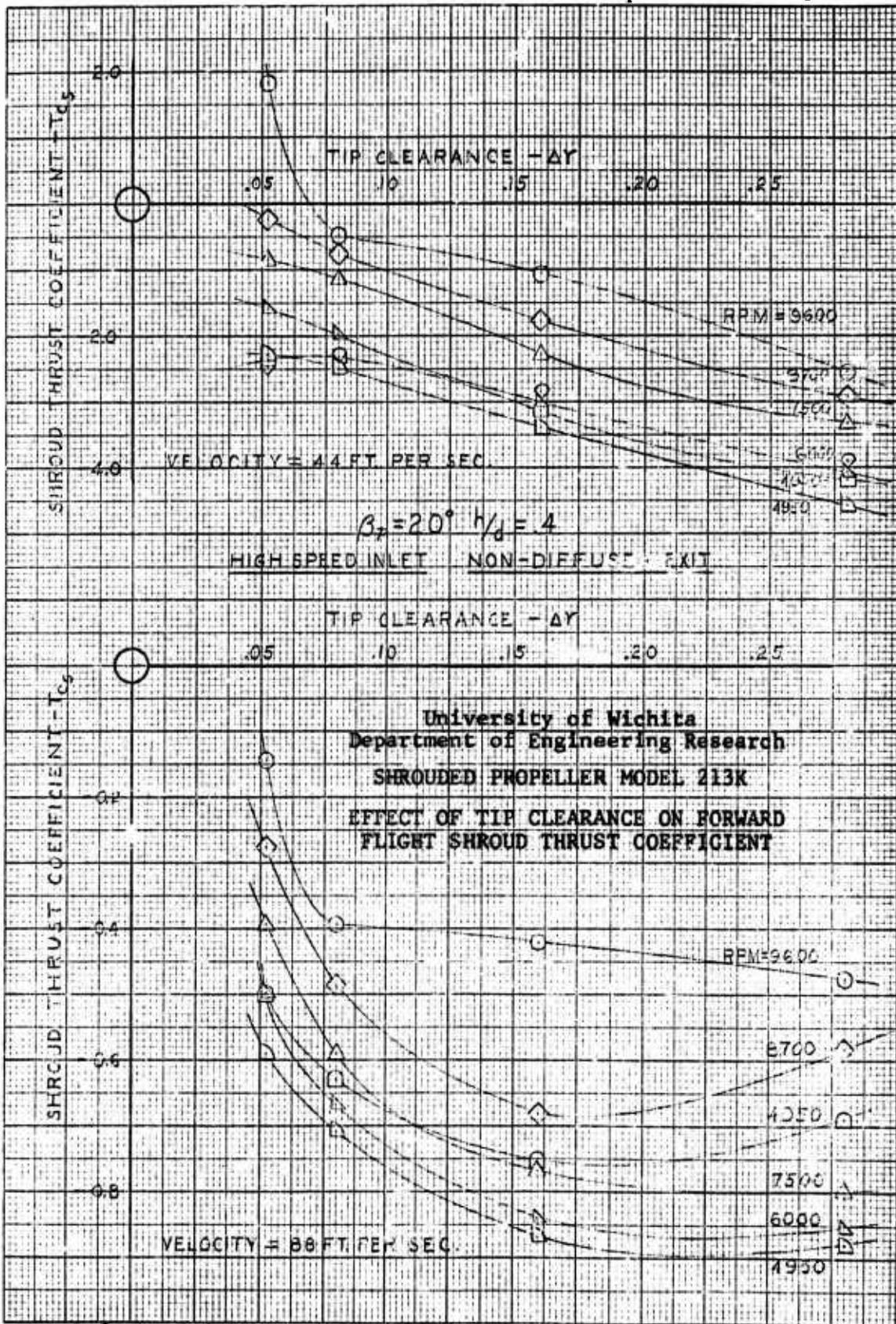
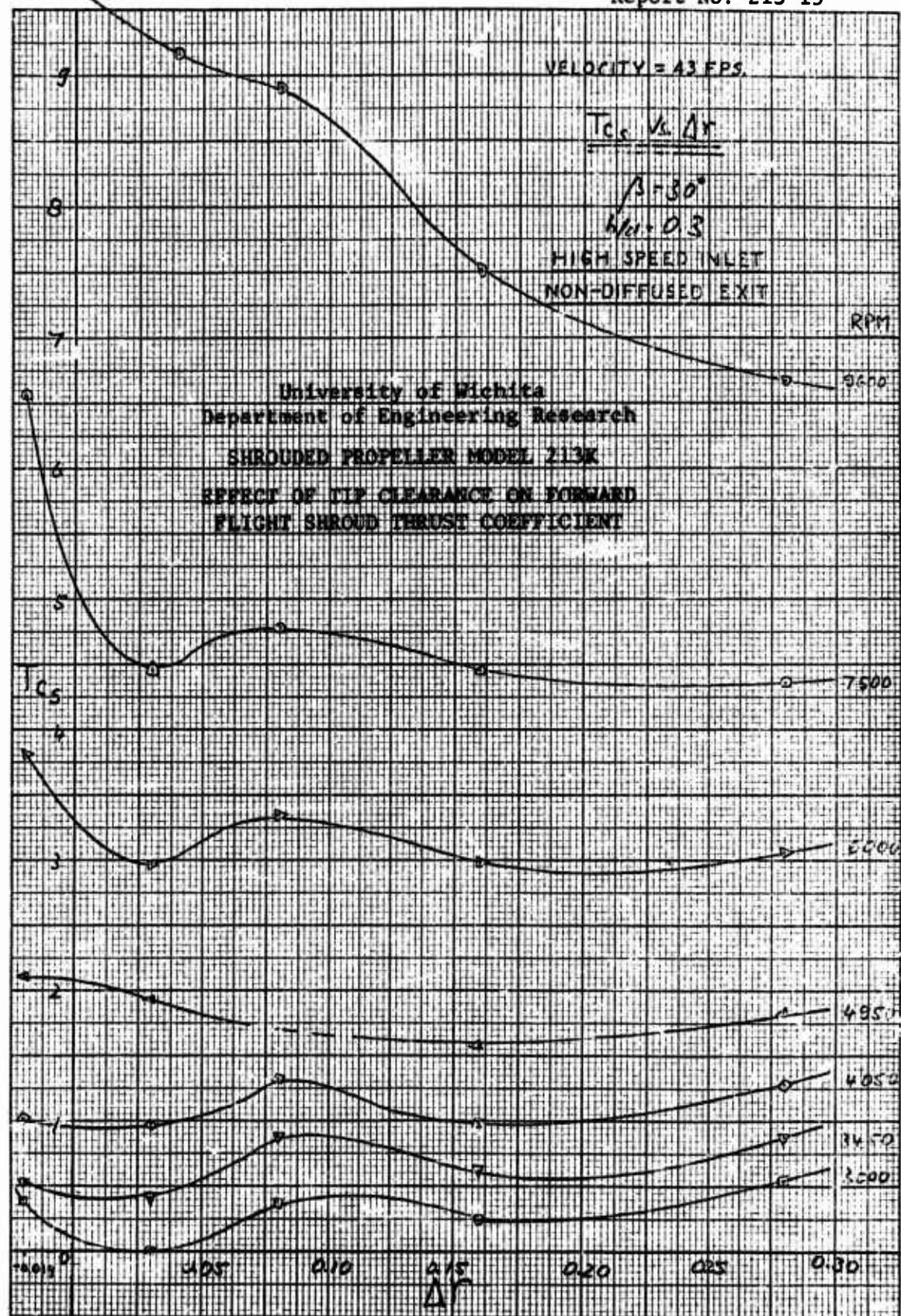


Figure 12 (cont'd)



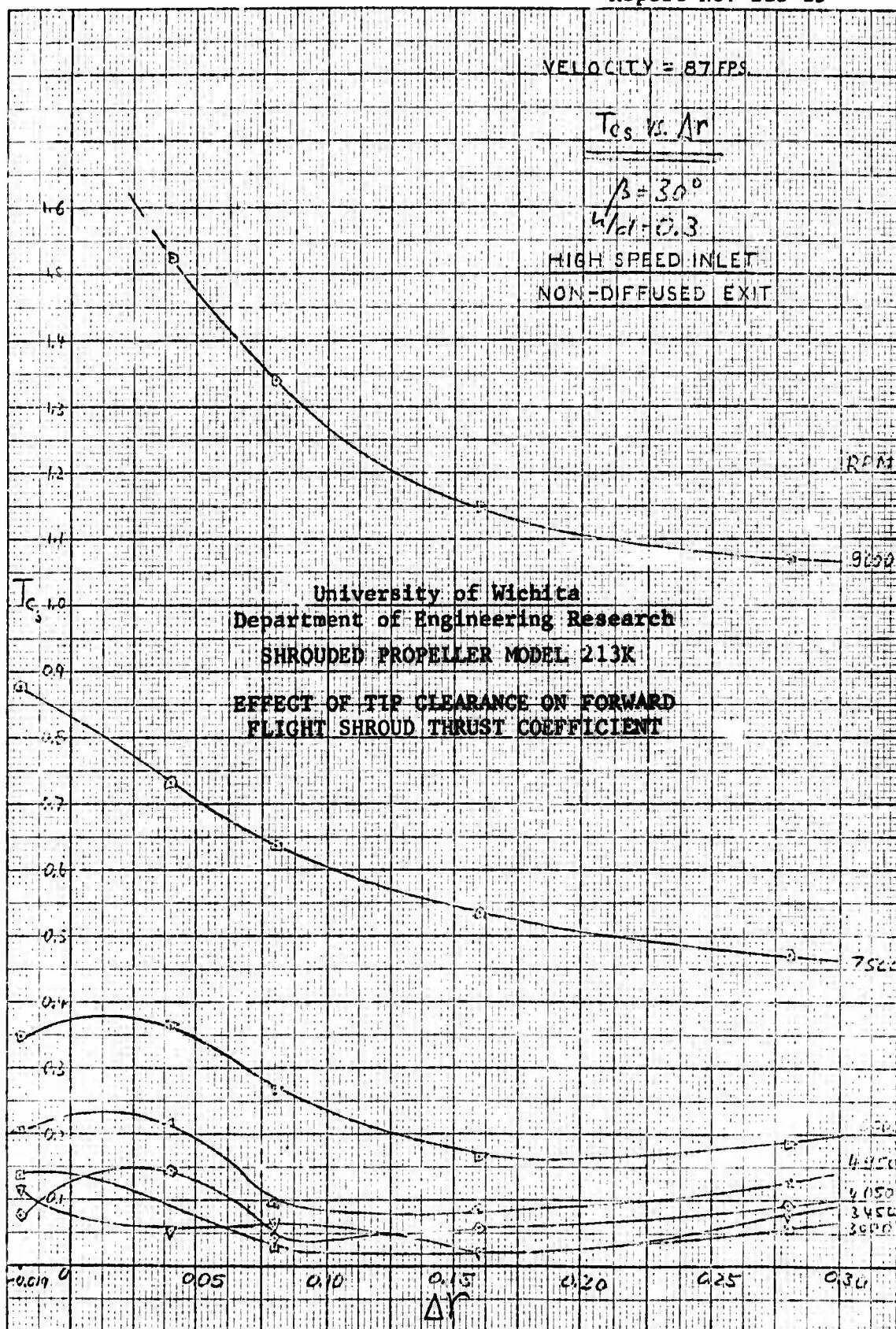
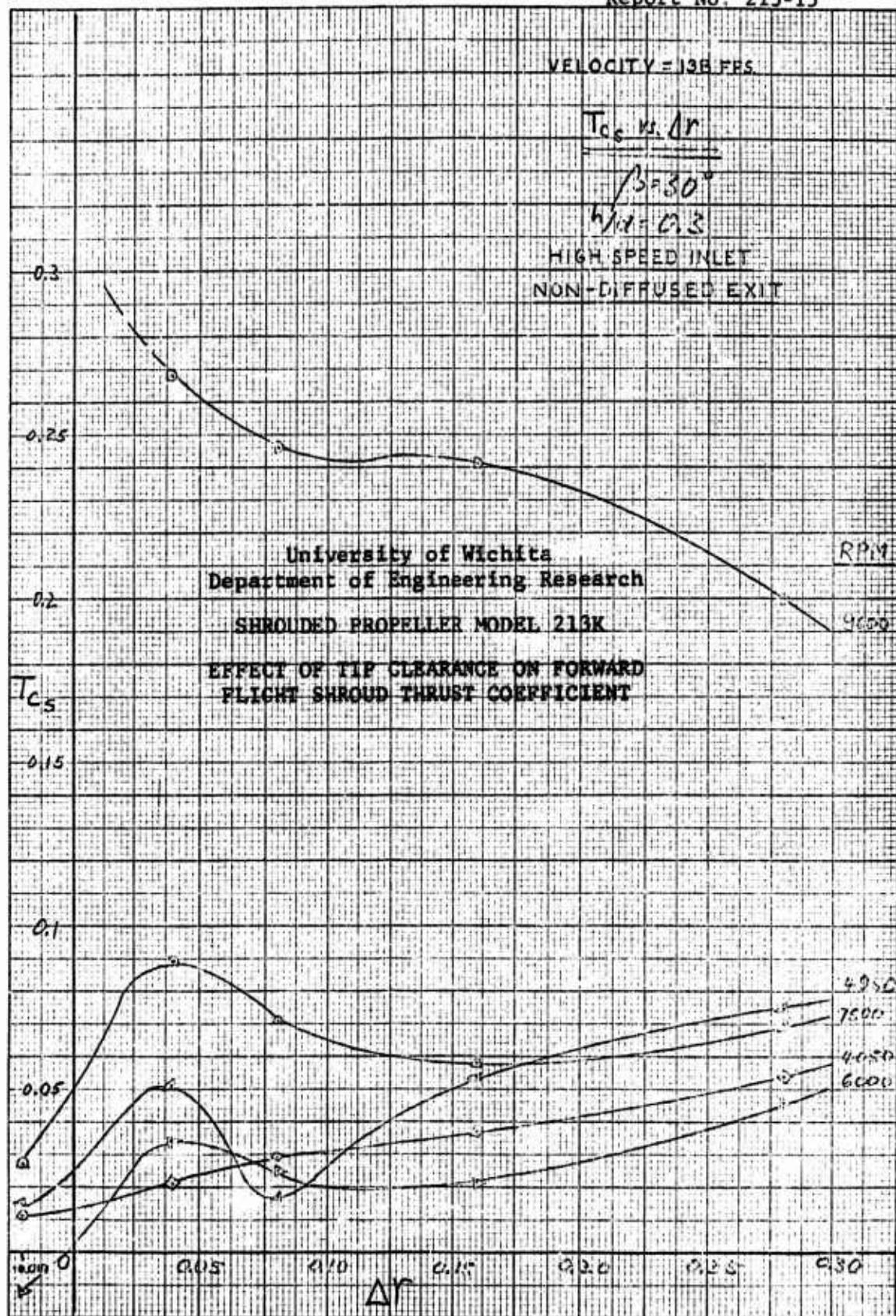


Figure 12 (cont'd)



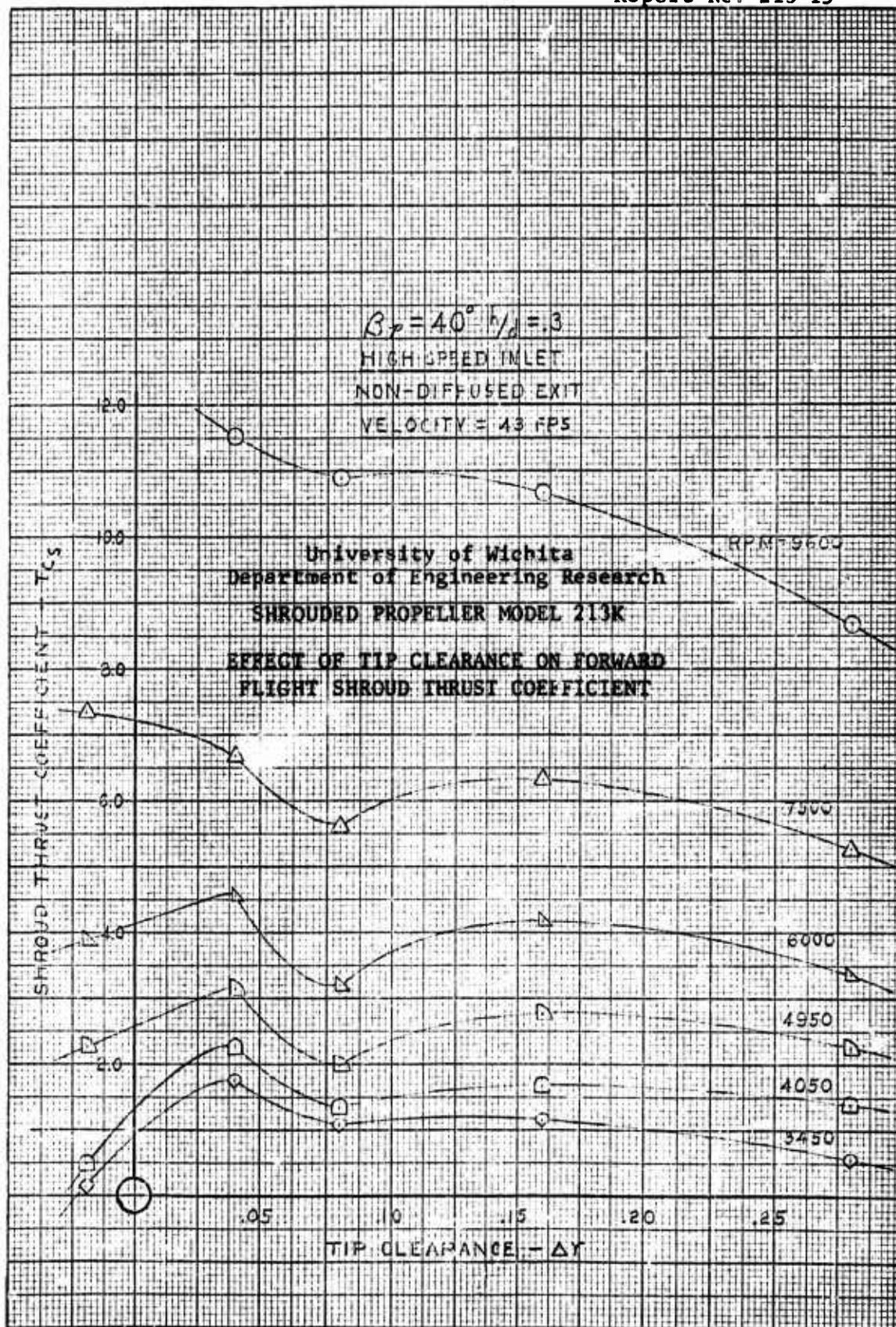


Figure 12 (cont'd)

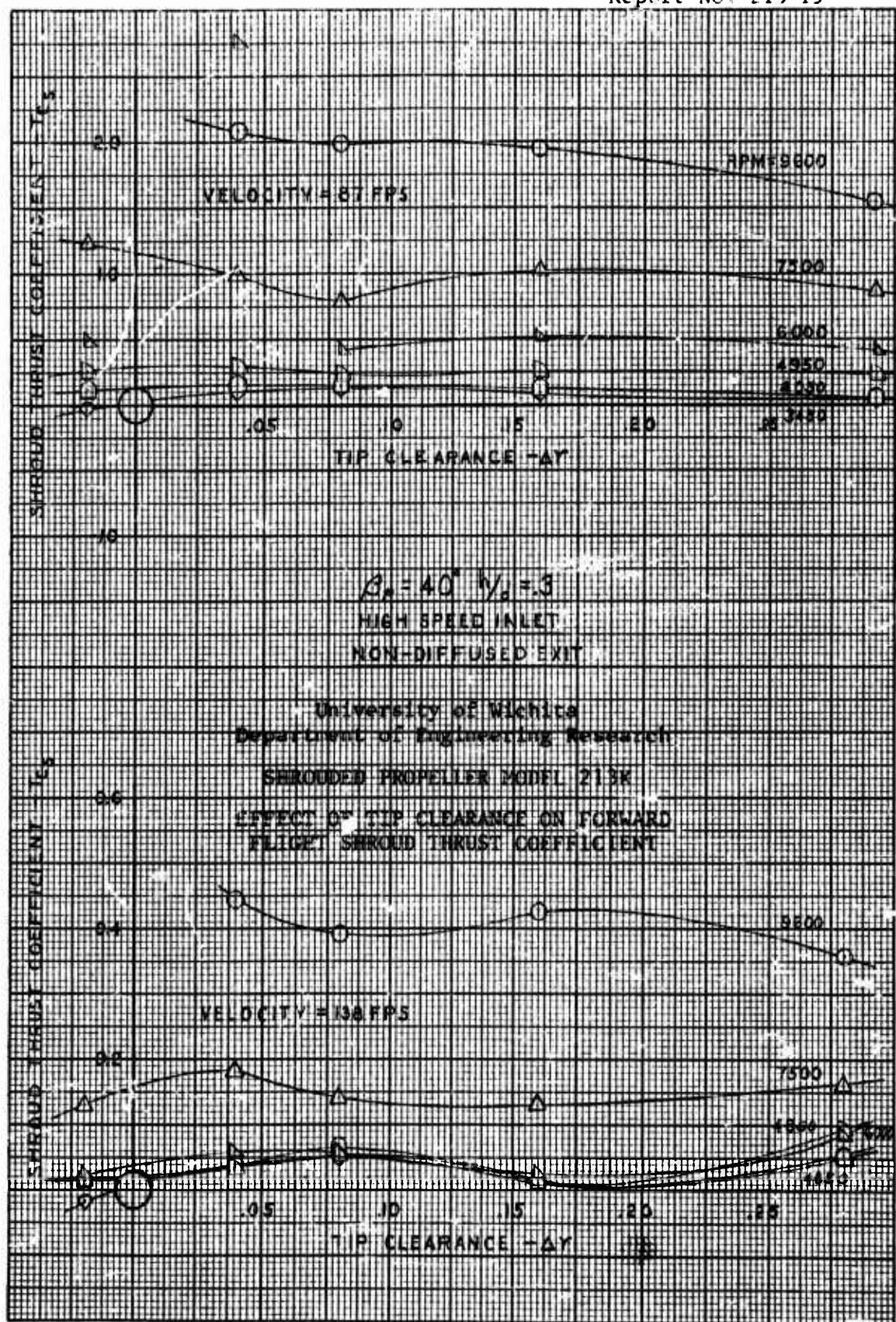


Figure 12 (cont'd)

University of Wichita
Department of Engineering Research

SHROUDED PROPELLER MODEL 213K

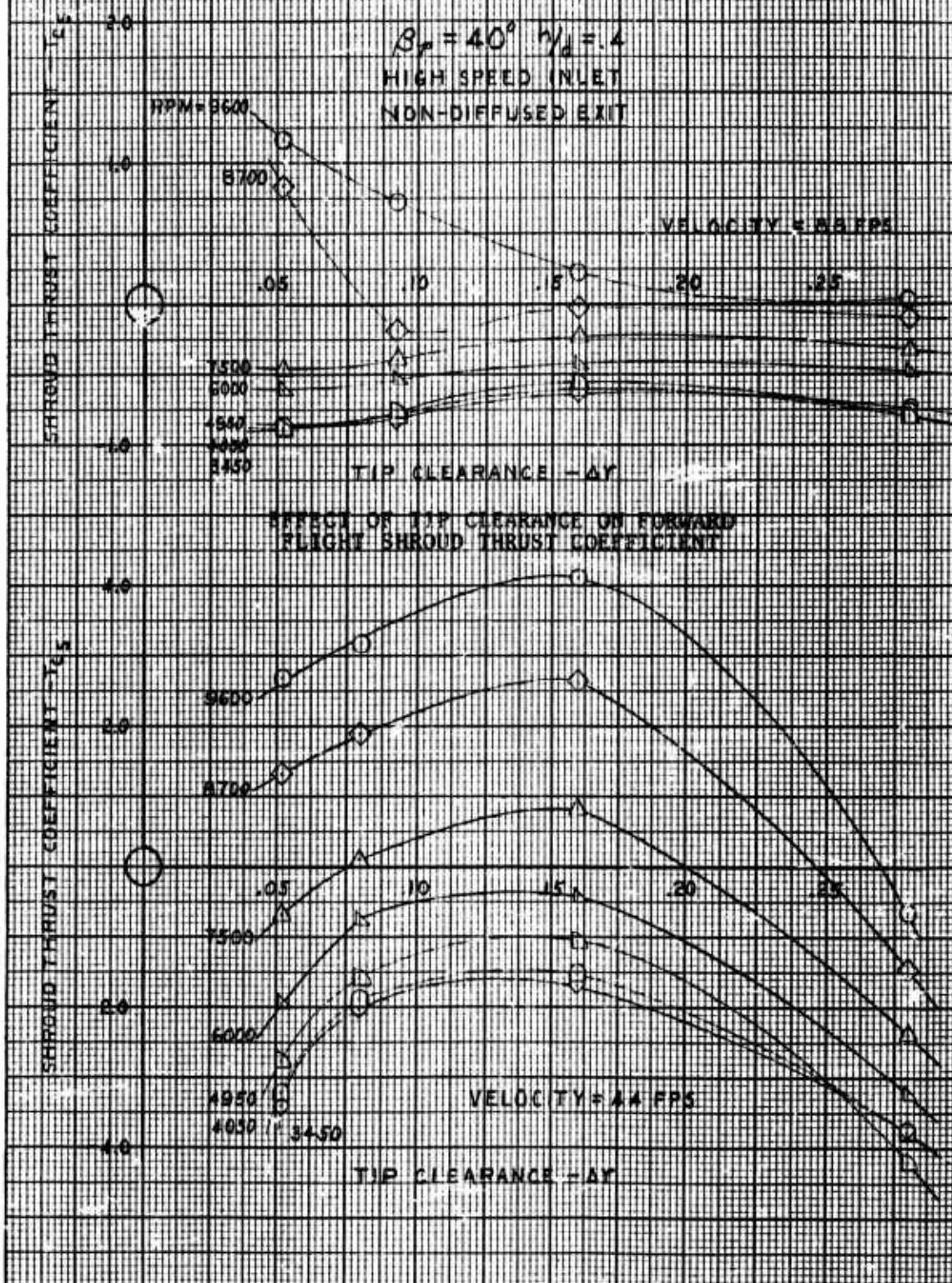
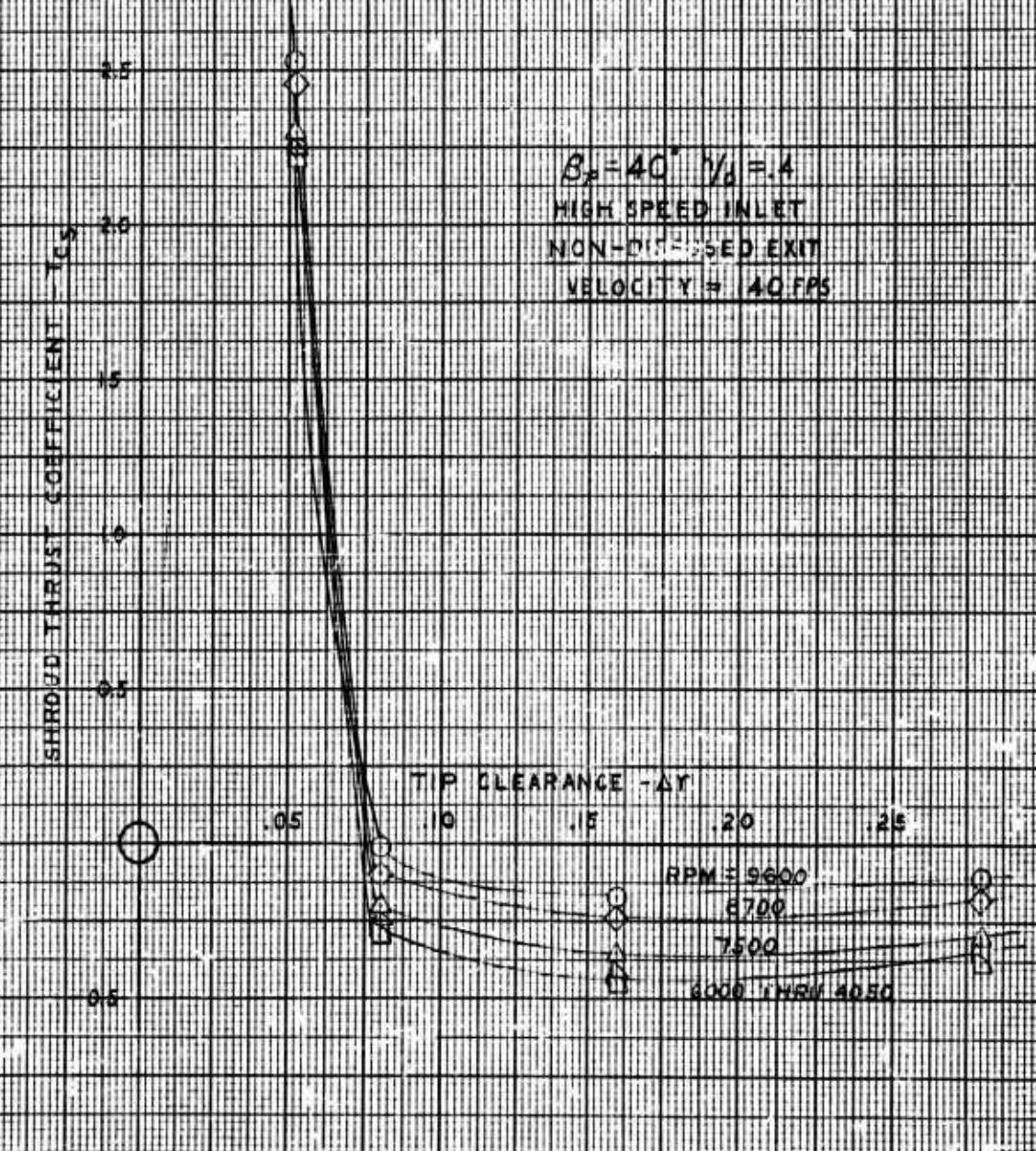


Figure 12 (cont'd)

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SHROUDED PROPELLER MODEL 213K

**EFFECT OF TIP CLEARANCE ON FORWARD
FLIGHT SHROUD THRUST COEFFICIENT**



University of Wichita
Department of Engineering Research

SHROUDED PROPELLER MODEL 213K

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT PROPULSIVE EFFICIENCY

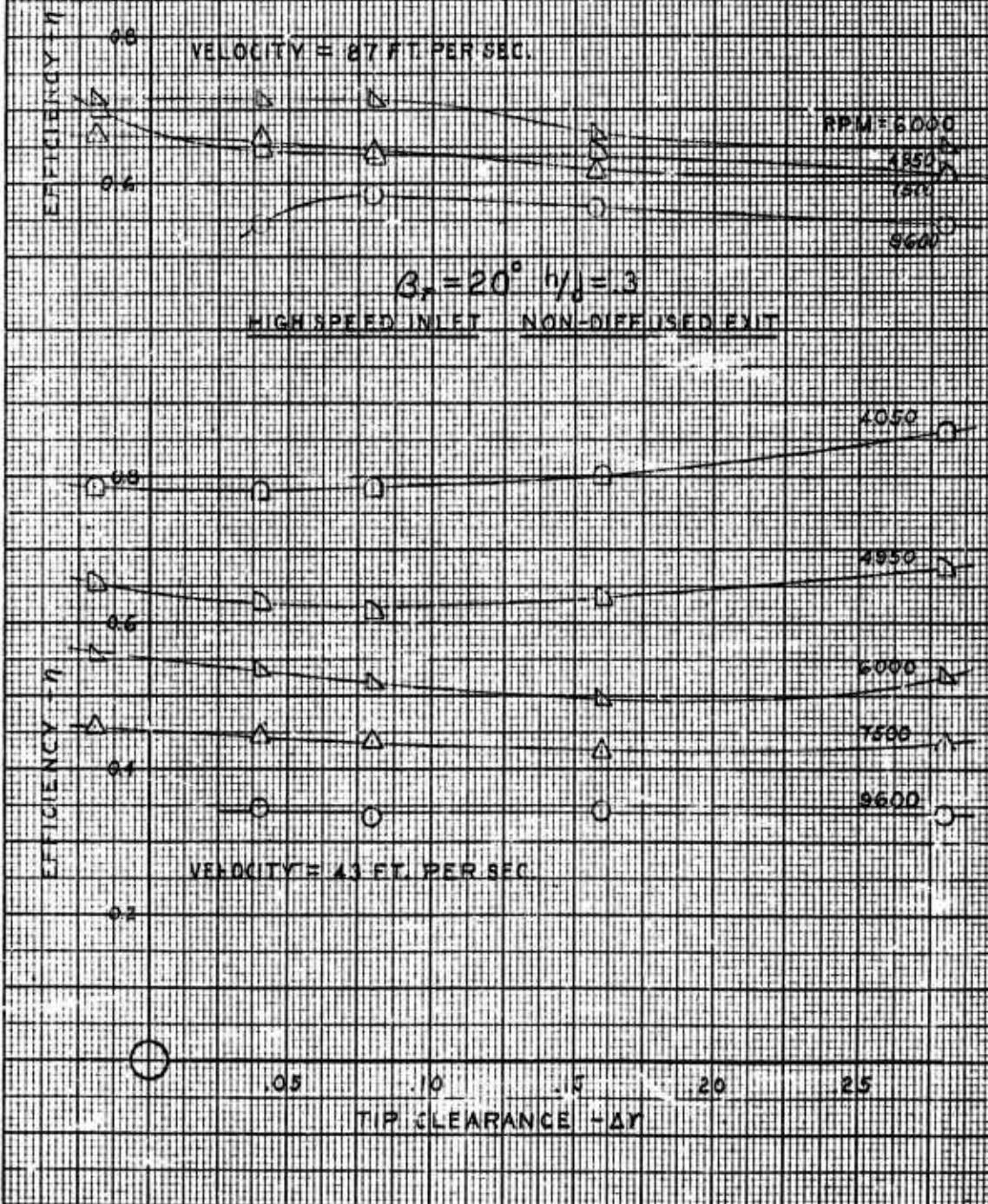
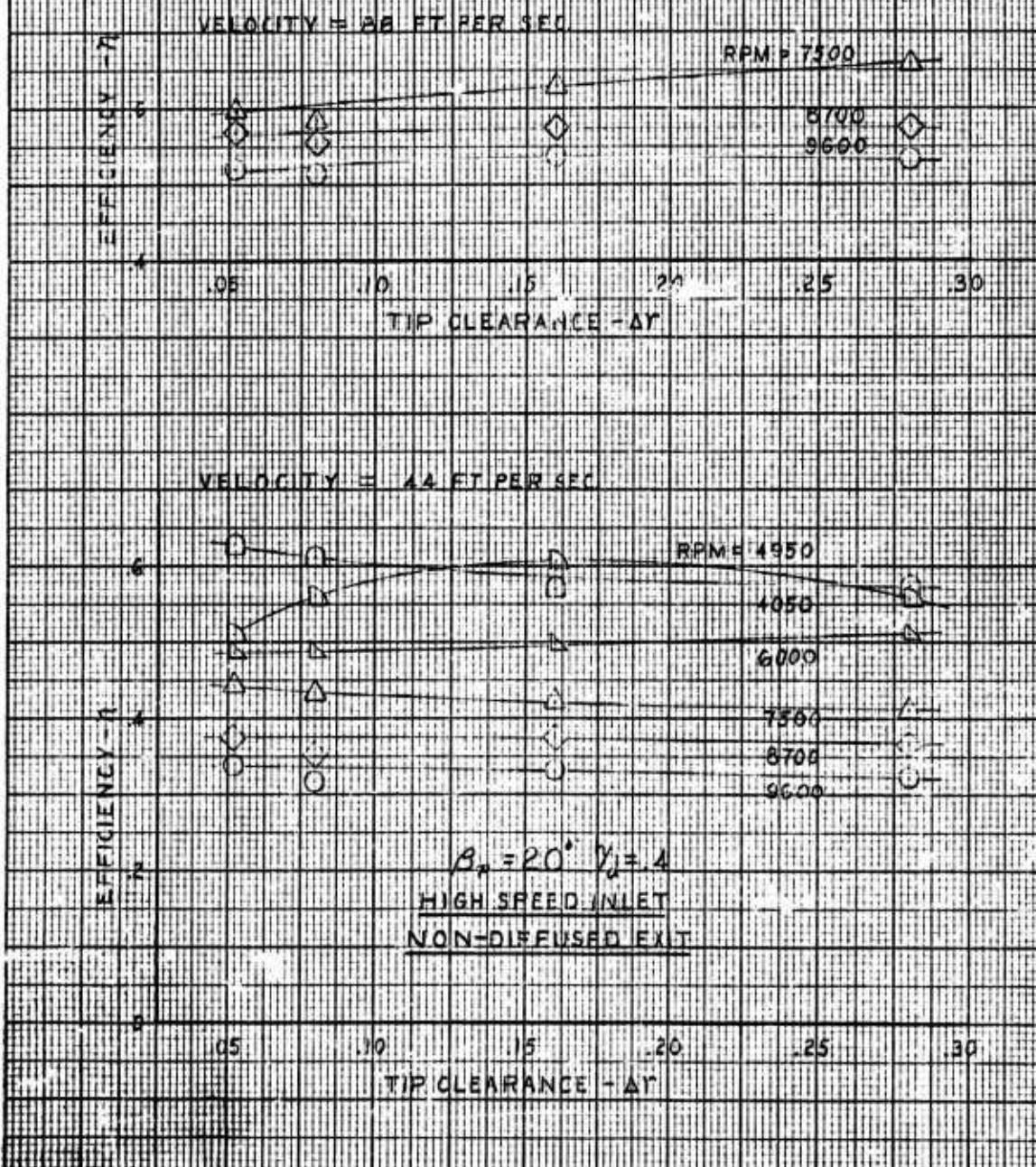


Figure 13

University of Illinois
Department of Engineering Research

SHROUDED PROPELLER MODEL 213K

EFFECT OF TIP CLEARANCE ON FORWARD
FLIGHT PROPULSIVE EFFICIENCY

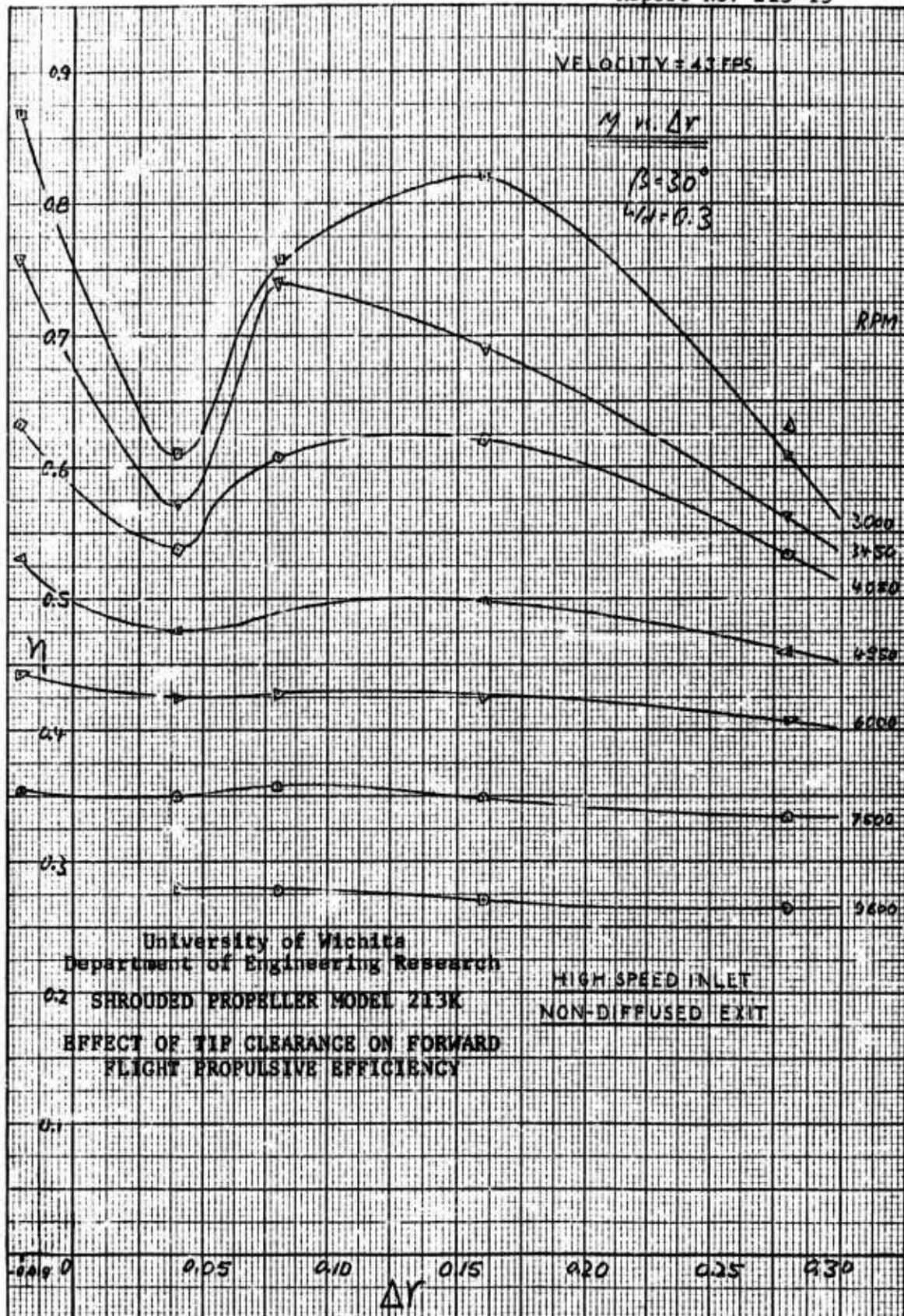
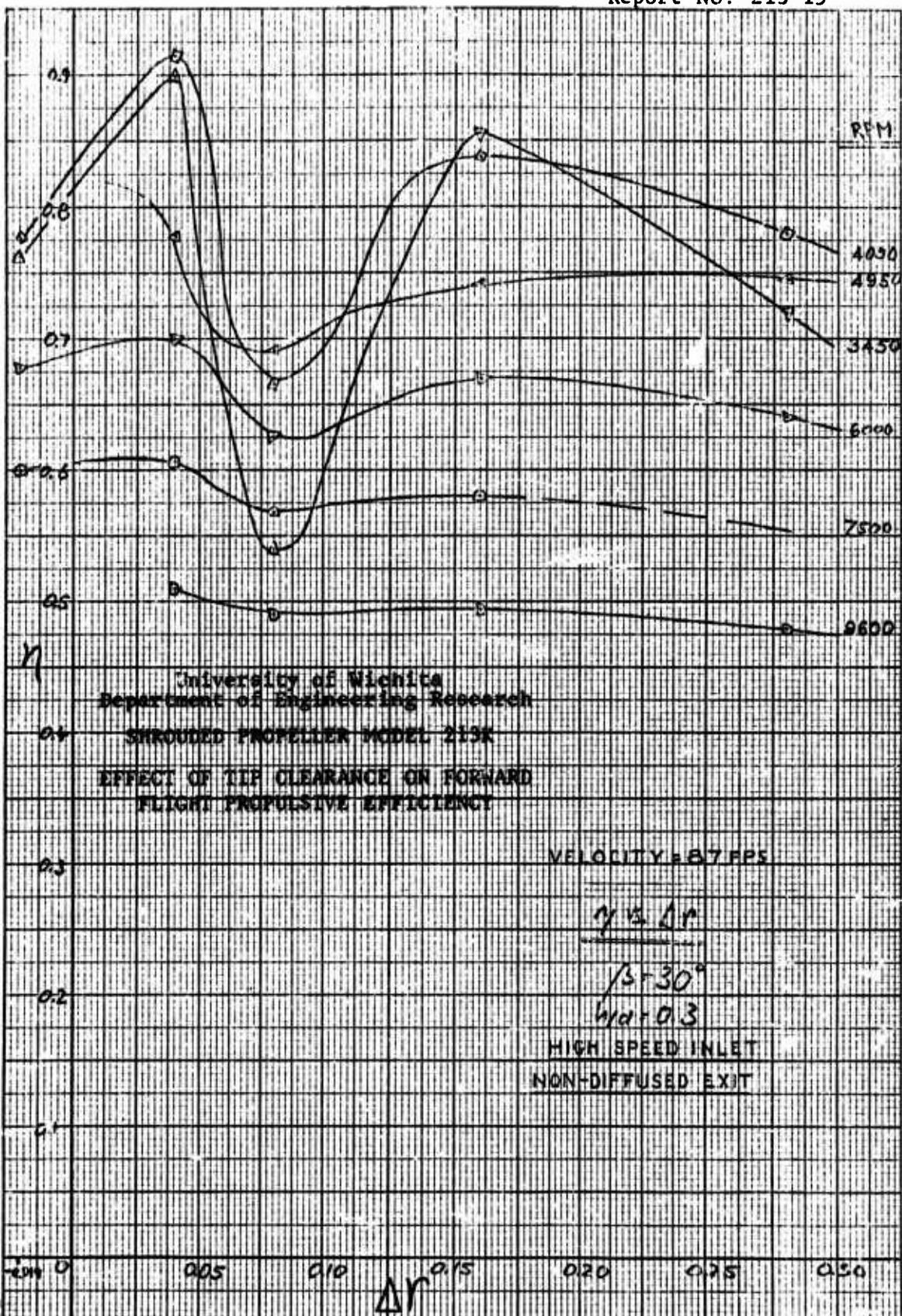


Figure 13 (cont'd)



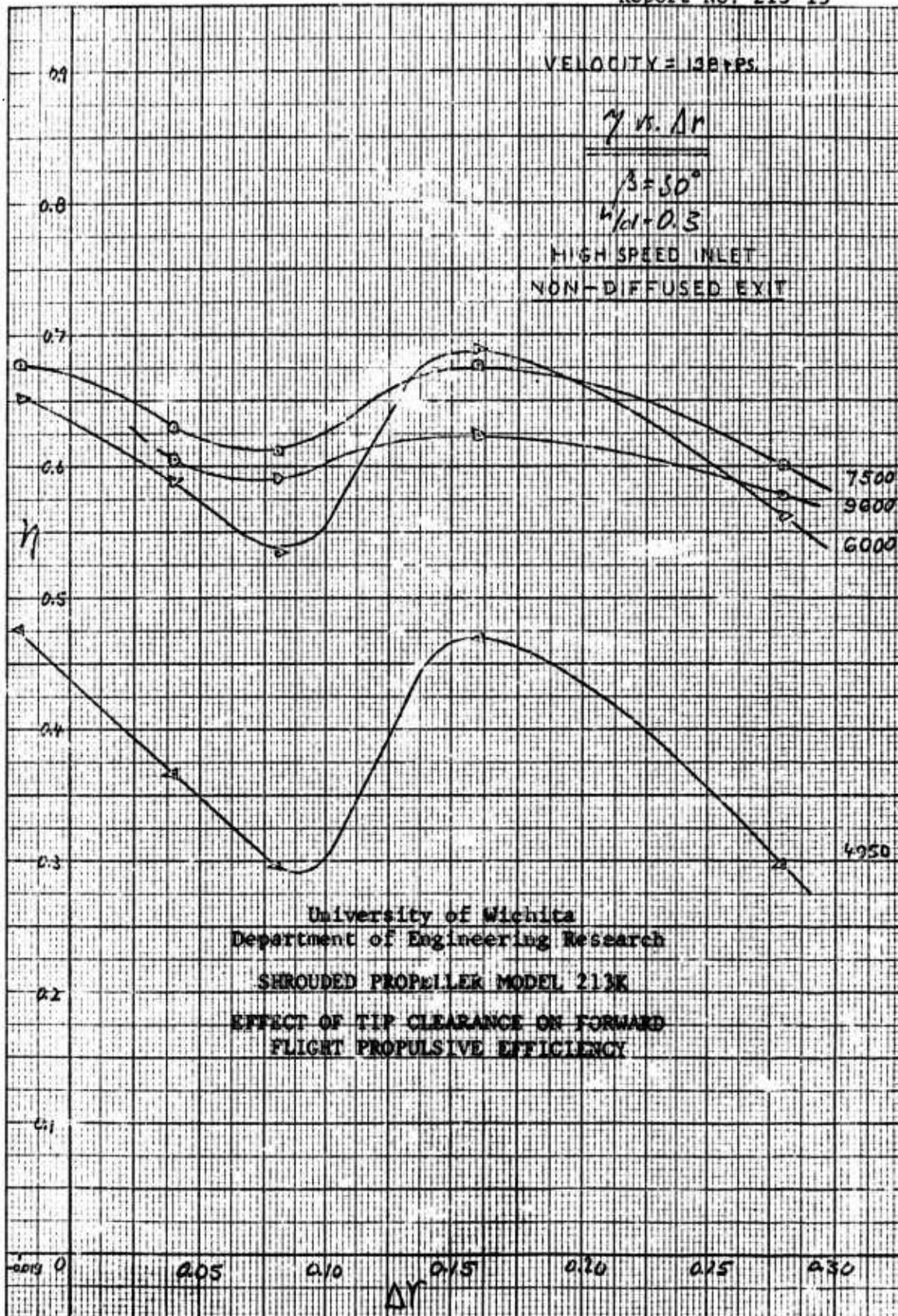
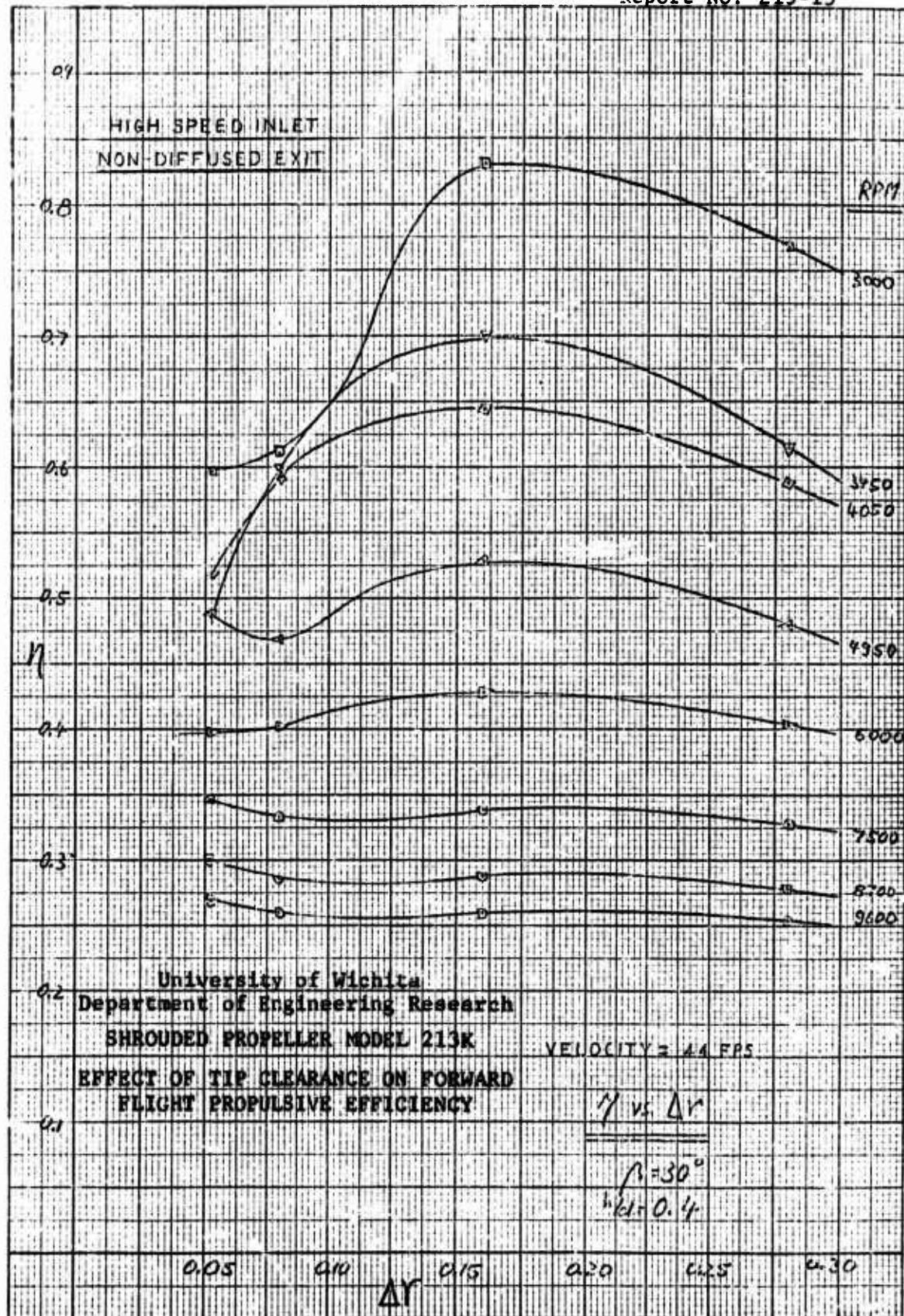


Figure 13 (cont'd)



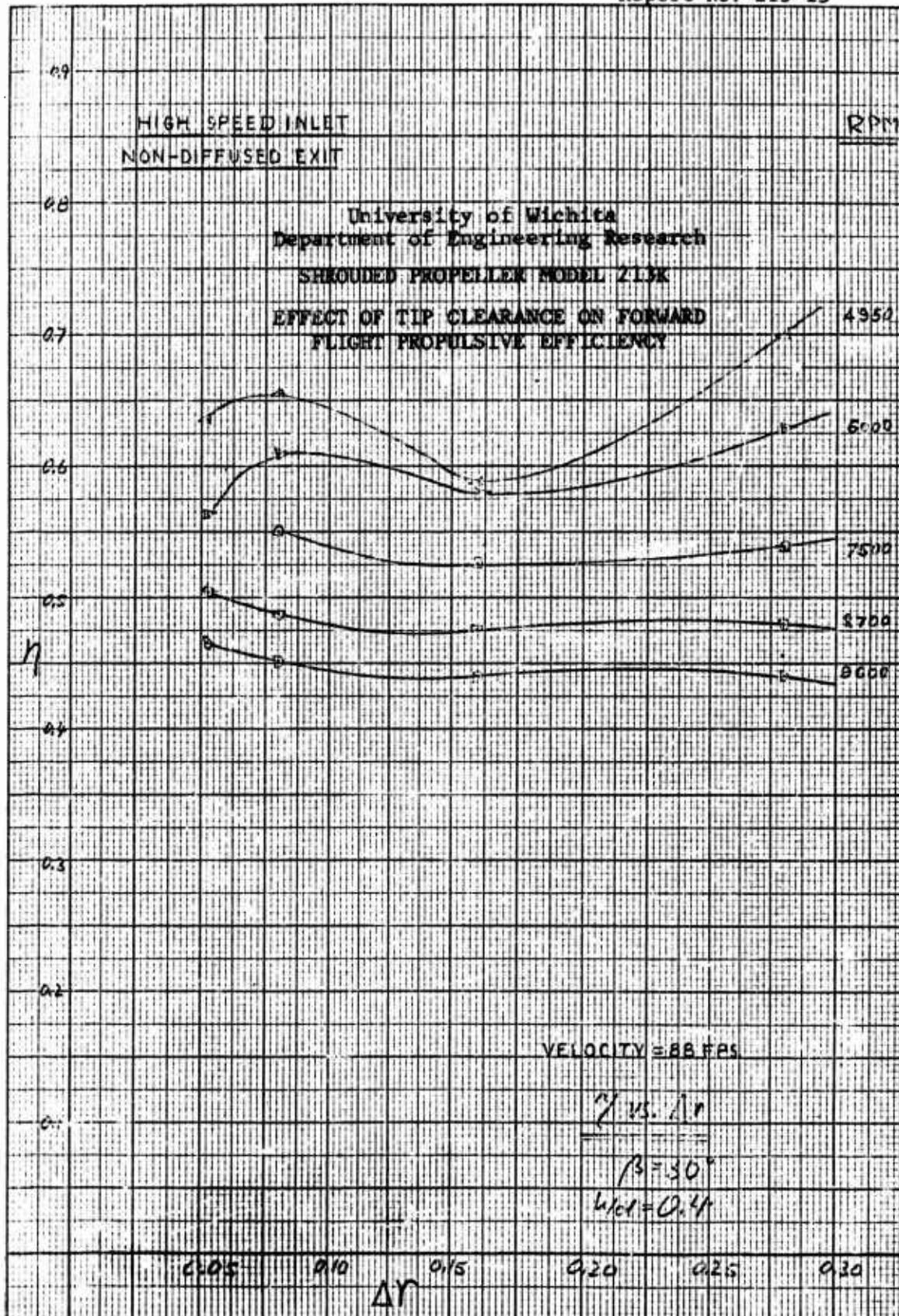
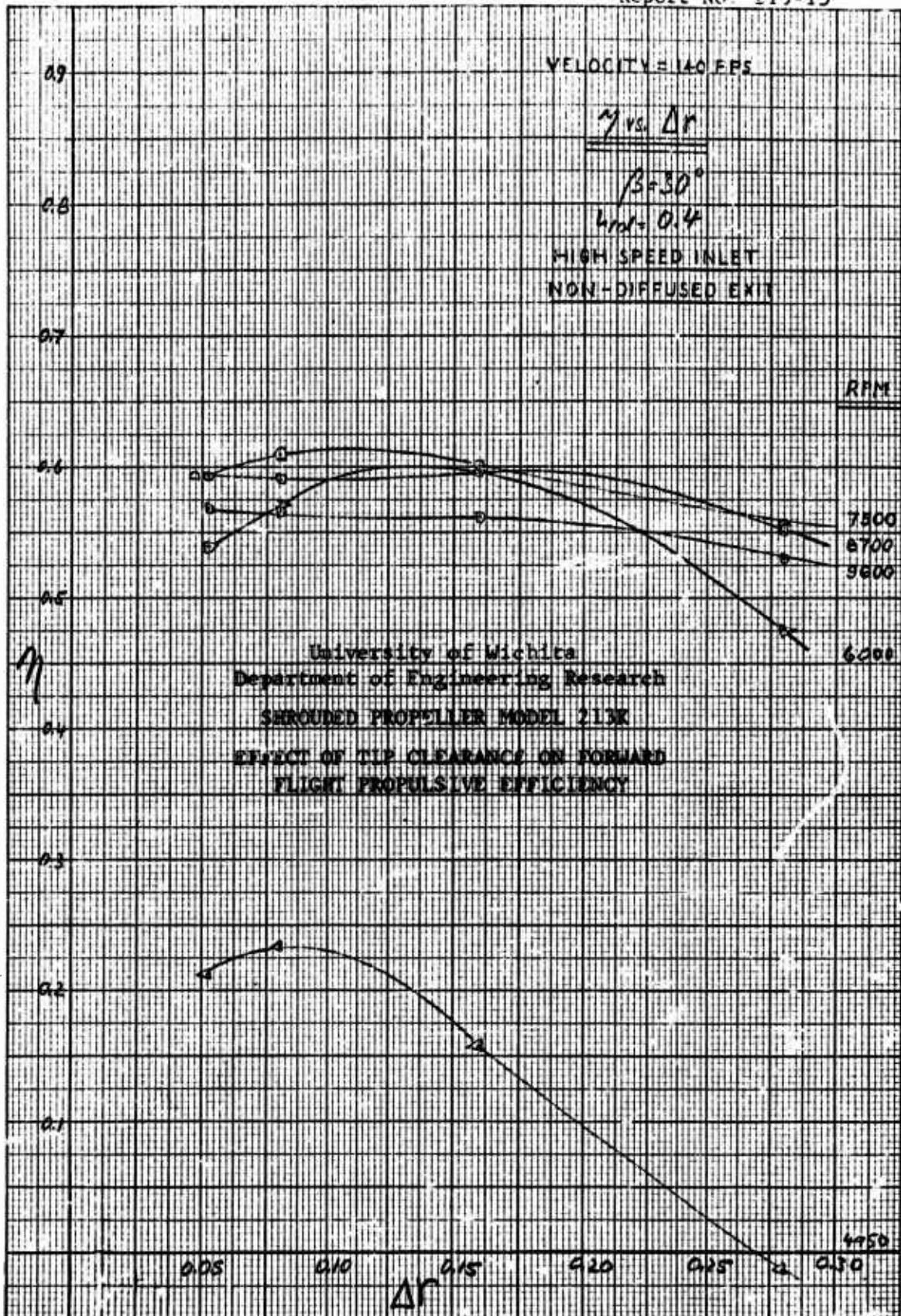


Figure 13 (cont'd)



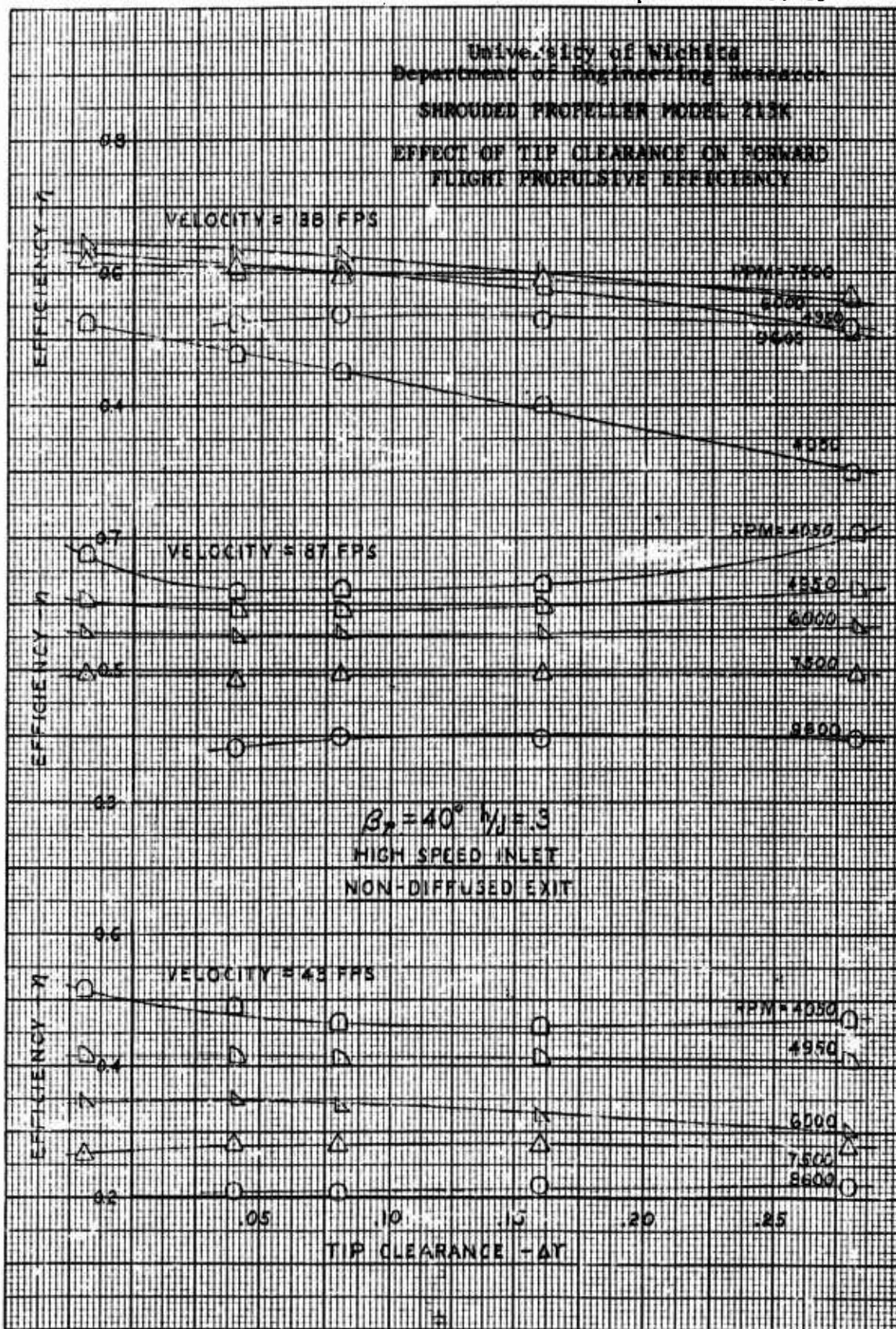


Figure 13 (cont'd)

University of Wichita
Department of Engineering Research
SHROUDED PROPELLER MODEL 213-15

EFFECT OF TIP CLEARANCE ON FORWARD FLIGHT PROPULSIVE EFFICIENCY

0.7

VELOCITY = 140 FPS

K₁K₂K₃K₄K₅K₆K₇K₈K₉K₁₀K₁₁K₁₂

RPM = 6000

△ - 7500

△ - 4950

○ - 3700

○ - 2600

$$\beta_p = 40^\circ \quad \gamma_0 = .4$$

HIGH SPEED INLET

NON-DIFFUSED EXIT

VELOCITY = 86 FPS

K₁K₂K₃K₄K₅K₆K₇K₈K₉K₁₀K₁₁K₁₂

○ - 4050

△ - 4950

○ - 3700

△ - 2600

○ - 1950

○ - 9600

VELOCITY = 44 FPS

K₁K₂K₃K₄K₅K₆K₇K₈

○ - 4050

△ - 4950

○ - 6000

△ - 7500

○ - 8700

△ - 9600

TIP CLEARANCE - ΔT